



# IRS 2000

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## The CloudSat Profiling O<sub>2</sub> A-Band Spectrometer/Imager (PABSI)

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July 2000



# Abstract

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The CloudSat mission was recently selected by NASA's Earth System Science Pathfinder (ESSP) Program. This satellite will be launched in 2003, and will fly in formation with the PICASSO-CENA Lidar Mission and the EOS-AQUA platform to provide the first comprehensive, global, 3-dimensional description of clouds and aerosols and their radiative effects. The primary instrument on CloudSat is a 94 GHz cloud profiling radar (CPR), which will provide detailed vertical profiles of both thin and thick clouds along the satellite's ground track. CloudSat also carries the Profiling A-Band Spectrometer/Imager (PABSI). This instrument incorporates an imaging O<sub>2</sub> A-Band spectrometer and 2-channel push-broom imager.

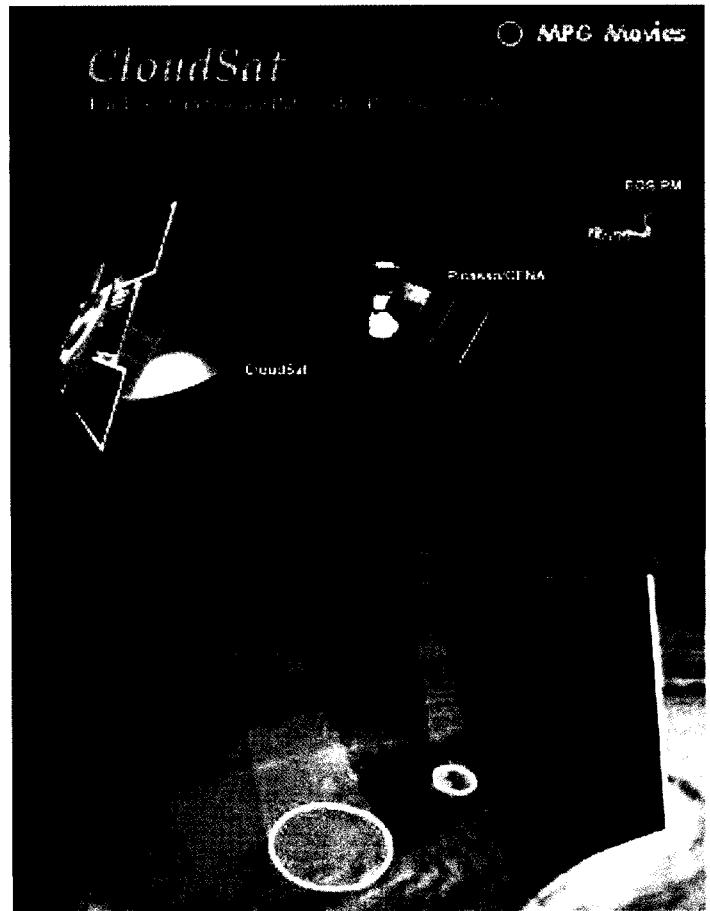
The PABSI spectrometer will acquire high-spectral resolution (0.03 nm) spectra of the O<sub>2</sub> A-band (759 to 772 nm). Its 120 mm f/2 foreoptics provide a spatial resolution of ~1 km along a 3 km wide cross-track swath that is centered on the CPR's 1.4 km footprint. This spectrometer will complement the CPR by characterizing the optical properties of clouds and aerosols at solar wavelengths and by constraining the cloud top height and geometrical thickness of low-level clouds that might be missed by the CPR. Its measurements will also provide estimates of optical depth and, can be combined with radar data to yield estimates of liquid and ice water contents of clouds.

The 2-channel push-boom imager provides a spatial resolution of ~0.5 km along a 15-km wide cross-track swath that is centered on the satellite's ground track. One of its two channels is centered at 747 nm, in a relatively transparent region of the spectrum that corresponds to an EOS MODIS channel (channel 15). The second channel is centered in the strong Q-R branch of the O<sub>2</sub> A-band at 761.5 nm. Because little solar radiation penetrates to the surface in this channel, it provides high signal to noise observations of high altitude clouds and aerosols, while minimizing interference from the surface. These two imaging channels will provide constraints on the spatial context and fine-scale structure of the clouds that are observed by the CPR and A-band spectrometer, and facilitate the registration of their data with the PICASSO-CENA and EOS AQUA observations of clouds and aerosols.



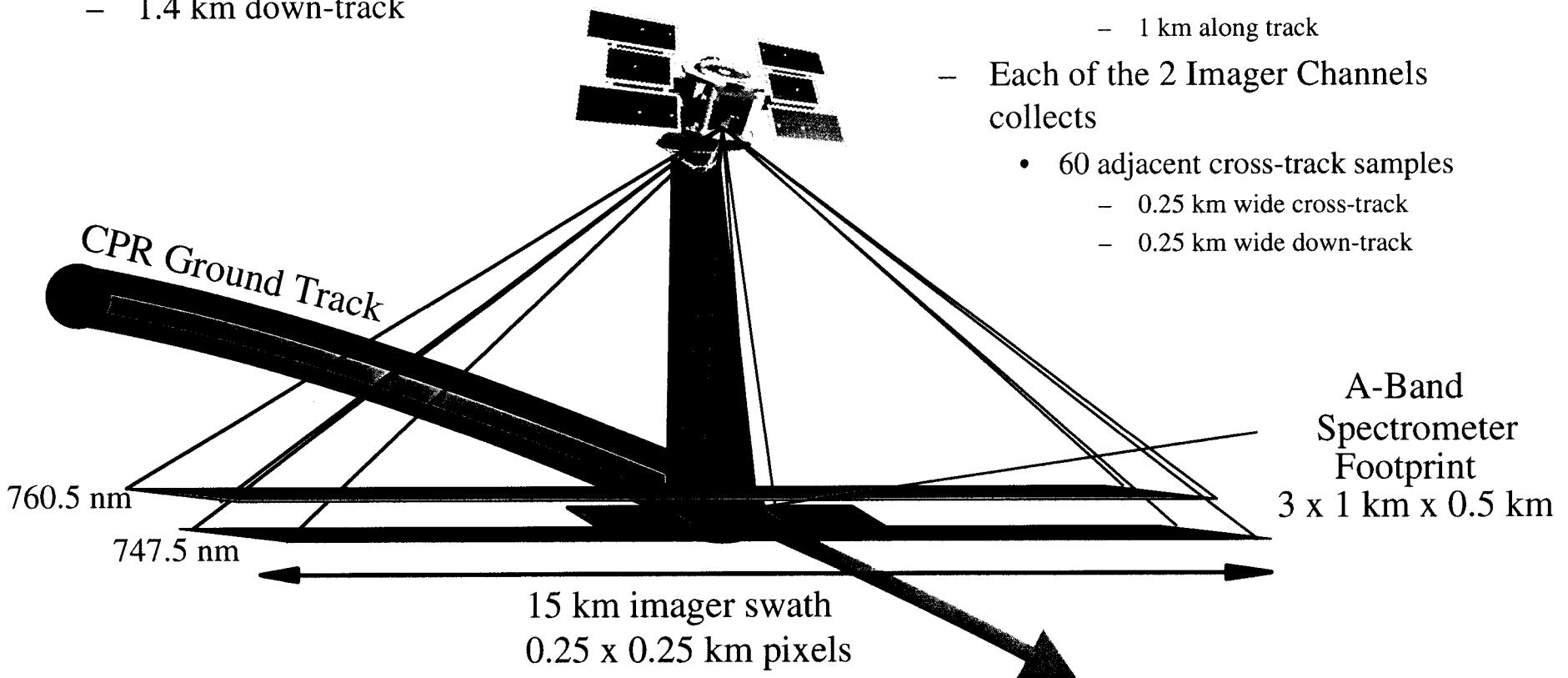
# The CloudSat Mission

- CloudSat will fly in a tight formation with the PICASSO-CENA Spacecraft, which in turn flies in formation with EOS Aqua
  - Near polar ( $98^\circ$ )
  - sun-synchronous
  - 704 km altitude
- CloudSat carries 2 scientific instruments
  - 94 GHz Cloud Profiling Radar (CPR)
  - Profiling O<sub>2</sub> A-Band Spectrometer/Imager (PABSI)
- PABSI incorporates
  - A high spectral resolution (0.06 nm) imaging O<sub>2</sub> A-Band spectrometer
  - A 2-channel push-broom imager



# PABSI and CPR Sampling

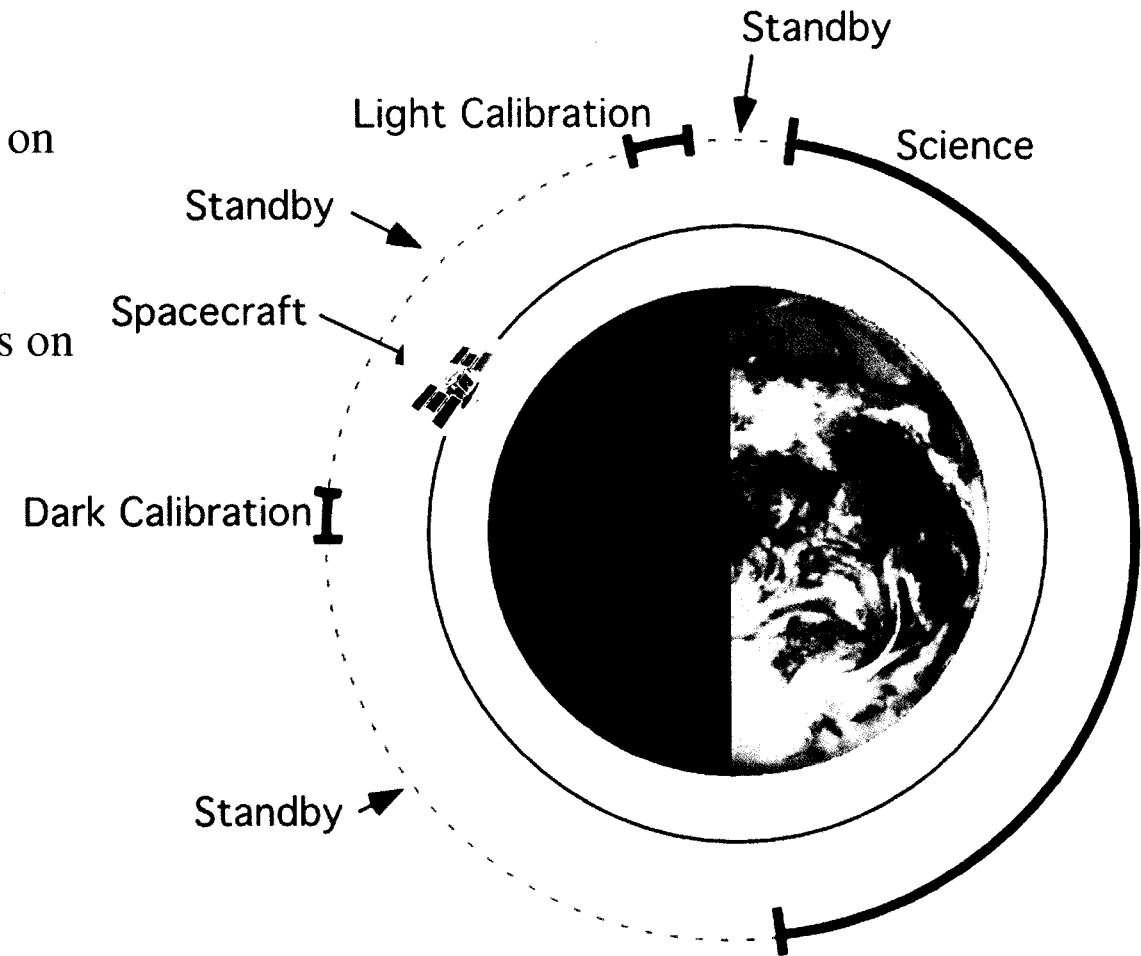
- The CPR acquires data along the CloudSat ground track
  - Single field of view
  - 1.4 cross-track
  - 1.4 km down-track



- The PABSI acquires data along the CloudSat ground track
  - Spectrometer collects data
    - 3 adjacent cross-track samples
      - 1 km wide cross-track
      - 1 km along track
    - Each of the 2 Imager Channels collects
      - 60 adjacent cross-track samples
        - 0.25 km wide cross-track
        - 0.25 km wide down-track

# PABSI Observing Modes

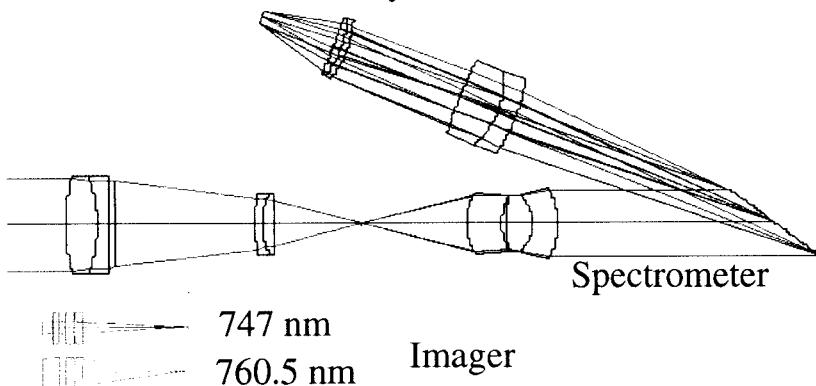
- PABSI science data
  - Collected while CloudSat is on the sunlit side of the Earth
- PABSI calibration data
  - Collected while Cloudsat is on the night side
  - Solar Calibration
    - Absolute radiometry
    - Flat fields for imagers
  - Dark Calibration
    - Bias and dark current



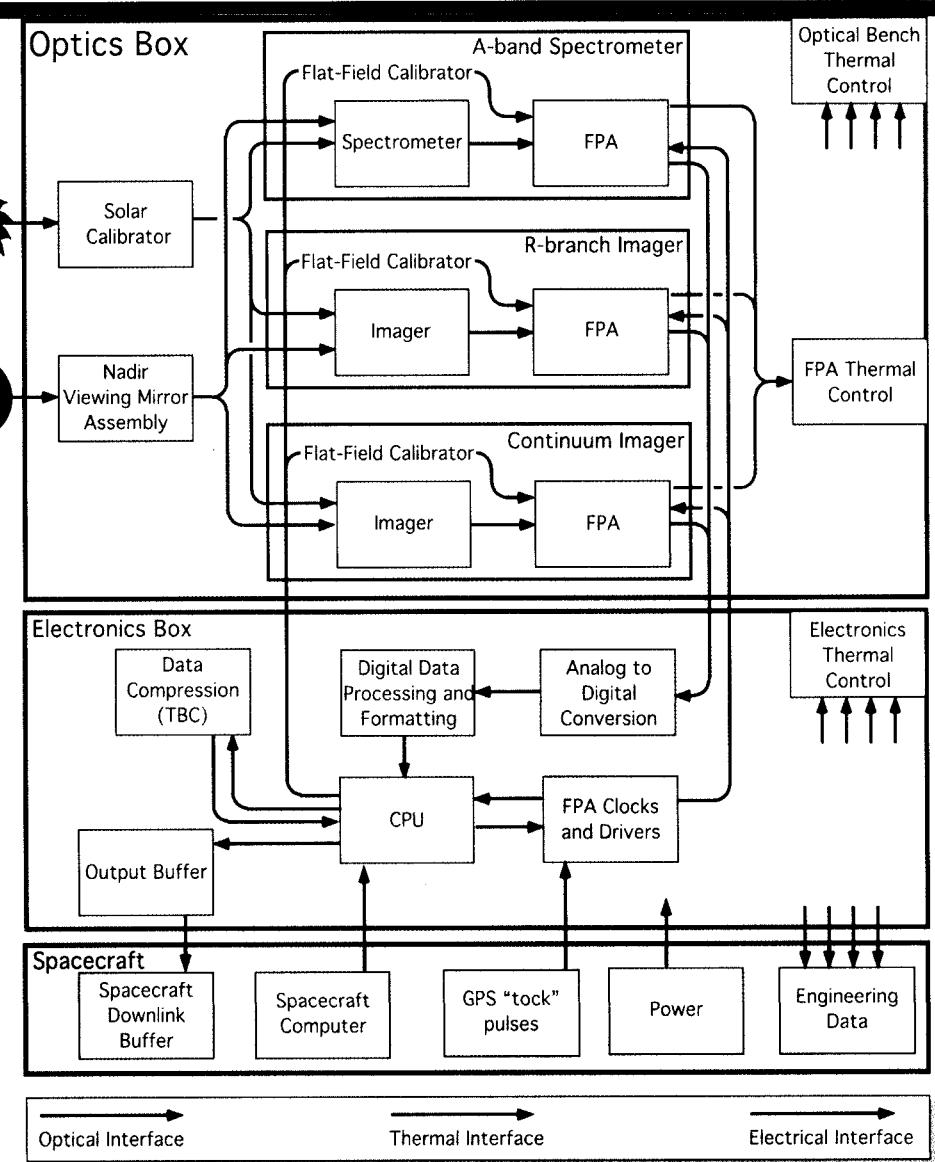
# PABSI Block Diagram

## PABSI incorporates

- A long-slit grating spectrometer
  - 120mm f/2 objective
  - 1.7 by 0.020 mm slit
  - refractive collimator
  - plane grating
  - camera assembly
  - 2-d CCD focal plane array
- 2 push-boom imagers
  - 40 mm f/4 objectives
  - CCD line arrays



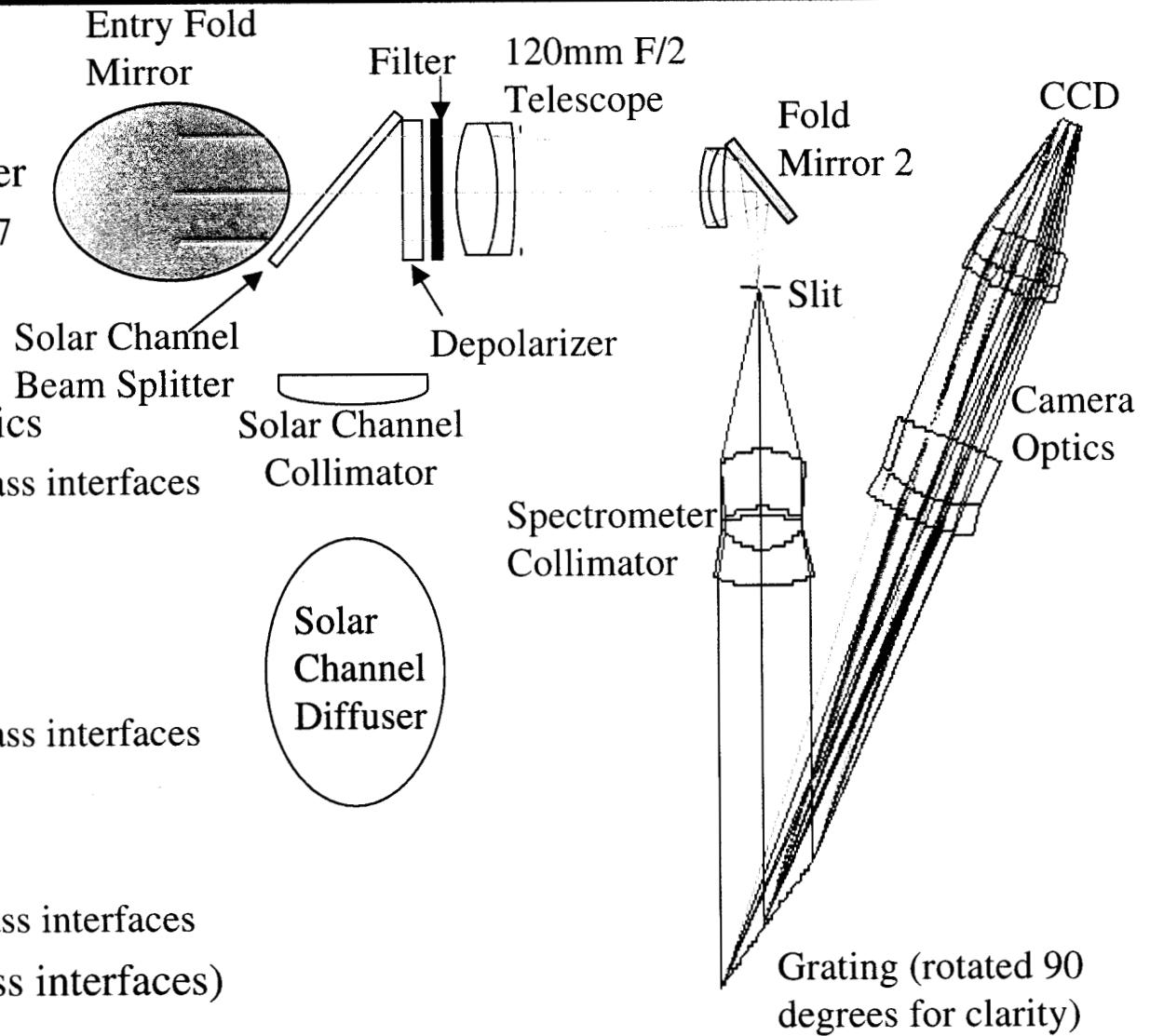
Optical Schematic for PABSI



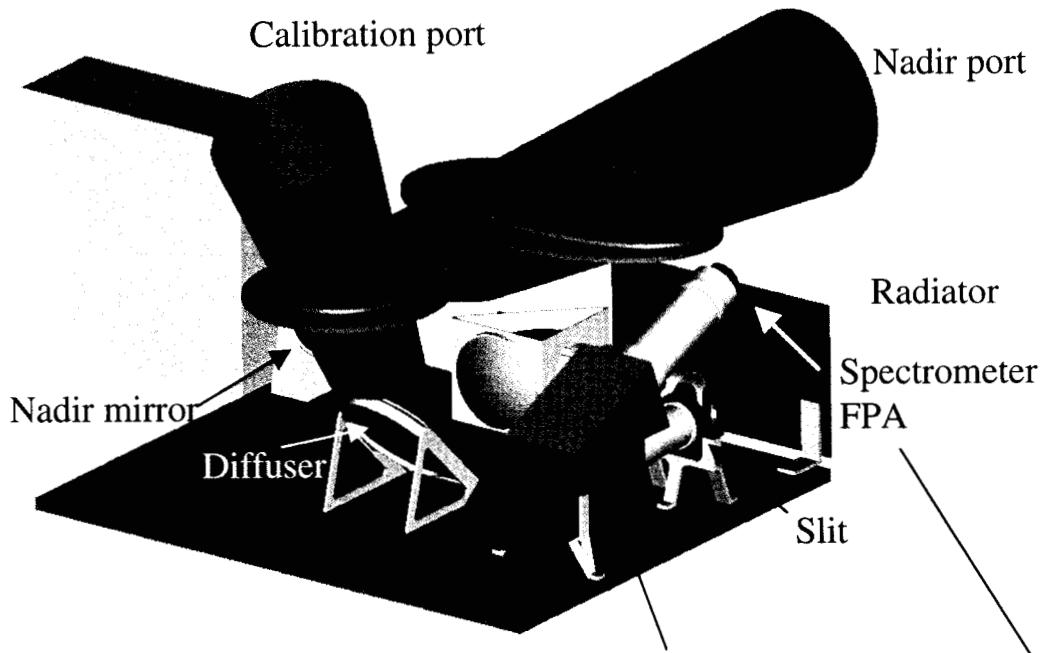
# PABSI Spectrometer Optical System

## Optical System Components

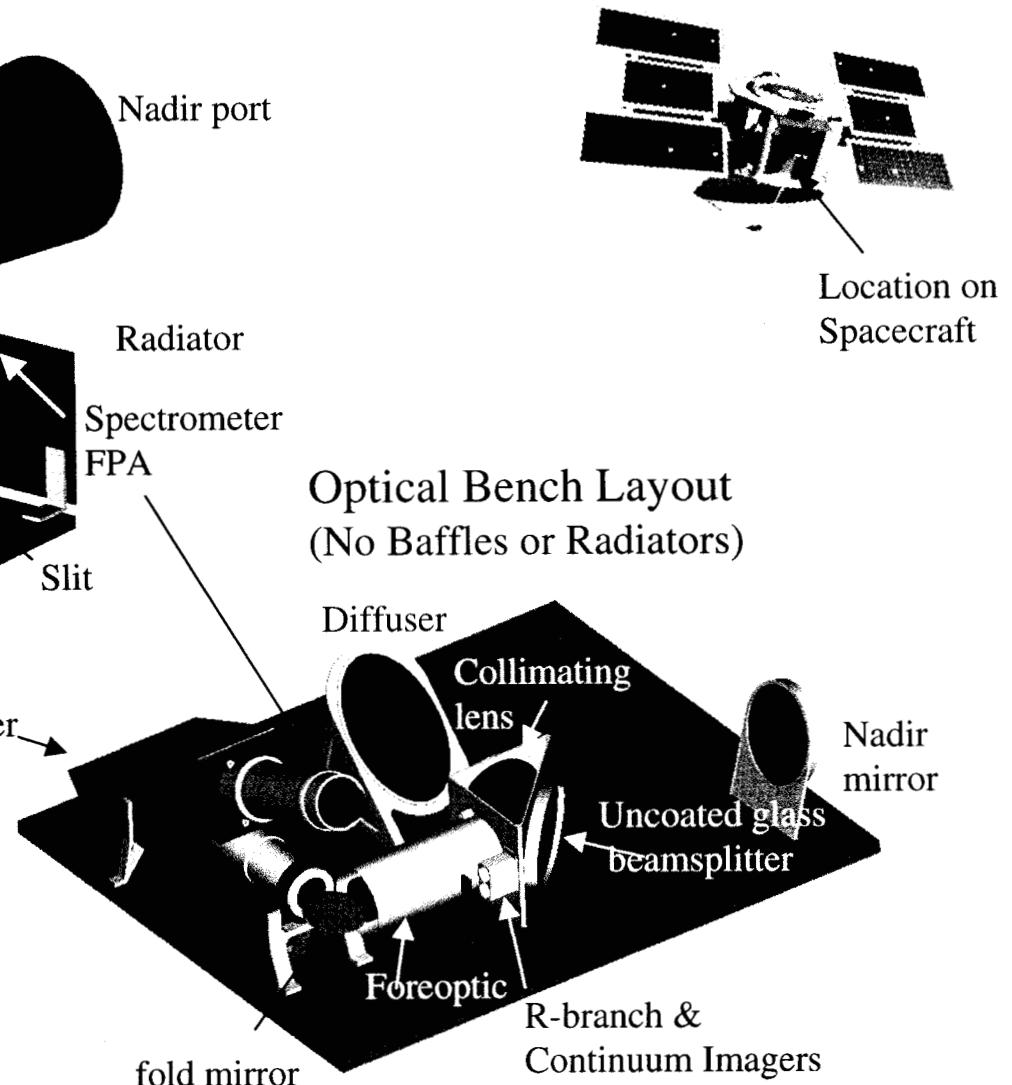
- Entry fold mirror
- Solar Channel Beam Splitter
  - 5mm thick, uncoated BK7
- Depolarizer
- Predisperser Filter
- 120mm F/2 Telescope Optics
  - 2 Doublets, 4 vacuum-glass interfaces
- Fold Mirror 2
- Slit (0.01 by 1.7 mm)
- Collimator
  - 3 elements, 4 vacuum-glass interfaces
- Grating
- Camera Optics
  - 2 doublets, 4 vacuum-glass interfaces
- CCD (QE + 2 vacuum-glass interfaces)



# PABSI Layout (Preliminary)



Optical Bench Layout  
(Showing Nadir and  
Calibration Baffles)



Optical Bench Layout  
(No Baffles or Radiators)

Location on  
Spacecraft

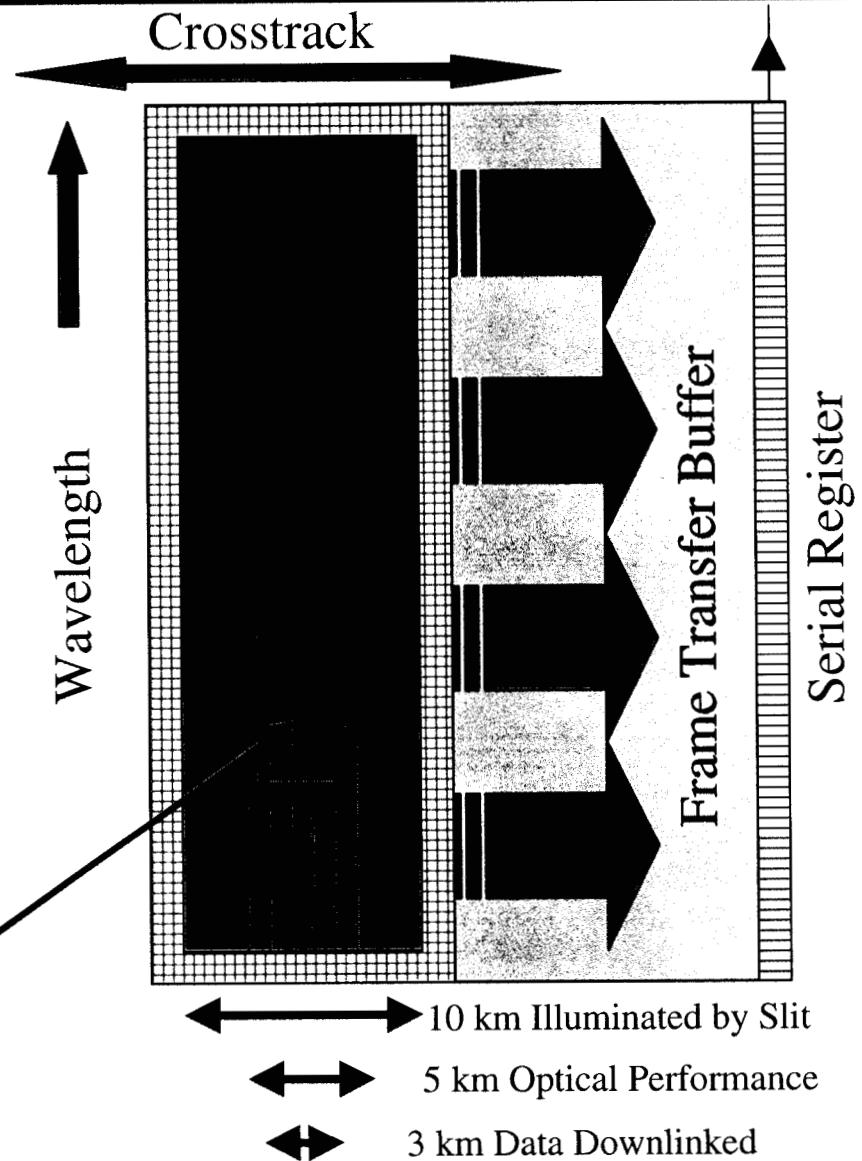
# PABSI Spectrometer Data

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- The mean spacecraft ground-track velocity will be 6.788 km/second
- The PABSI Spectrometer's down-track sampling rate matches the CPR's rate of 6.25 Hz, yielding a down-track IFOV of 1.086 km.
  - At each point, O<sub>2</sub> A-Band spectra will be taken for 3, adjacent, 1-km wide cross-track points within a 5-km wide region centered on the spacecraft's nadir point
  - The central point will be aligned with the CPR's footprint
- Number of spectral elements in each PABSI spectrum is constrained by the 125 kilobit/second data downlink data rate limitation
  - Includes 90 kilobits/second for the Spectrometer, 30 kilobits/second for the imager
  - If spectra are stored as 16-bit words, the 90 kilobit/second data rate accommodates 300 elements/spectra
  - If spectra are stored as 14-bit words, the 90 kilobit/second data rate accommodates 340 elements/spectra (roughly 1/3 of full array)
- This data rate produces the following data volumes (assumes no compression):
  - 291.6 Megabits/100-minute orbit or 4.2 Gibabits/day
    - assumes 50 minutes of science data
    - 4 minutes of calibration

# PABSI Spectrometer Focal Plane

- The focal plane is resolved into 1024 spectral elements and 256 cross-track elements
- The 1.7mm long slit illuminates a 10 km wide cross-track swath
  - Optical performance specifications must be met over central 5 km
  - Cross-track field of view is resolved into 3 1 km wide elements
    - Each crosstrack element consists of 14 12-micron pixels
- The 125 kbs Telemetry buget limits the number of spectral samples to
  - three 1kmwide cross-track elements, (nominally centered on CPR footprint)
  - ~320 of the 1024 spectral samples





# System Throughput Requirements

## Science Requirements that affect system throughput

- The A-Band spectrometer shall
  - cover the spectral range 760-770 nm;
  - have a resolution of  $1 \text{ cm}^{-1}$  or better;
  - have a SNR greater than 100:1 for a 5% reflecting surface
  - have out-of-band rejection characteristics of  $10^{-3}$ 
    - This will also require wavelength registration and characterization of the instrument slit function.
- The A-Band imager: shall have at least two narrow spectral bands
  - one centered at a wavelength near 747.5 nm
  - one centered at a wavelength near 760.5 nm
- CloudSat shall detect
  - all single-layer ice clouds with optical depth greater than 0.1
    - includes thin cirrus clouds over bright liquid water clouds or bright surfaces
  - all single-layer water clouds with an optical depth greater than 1.0
- CloudSat shall continuously measure the vertical structure of clouds along the nadir track of the satellite, with horizontal sampling  $\sim 1 \text{ km}$ .
  - The PABSI imager channels shall have a footprint  $<1/2$  the size of the radar footprint
- PABSI must be calibrated to 4% absolute accuracy and 2% relative accuracy

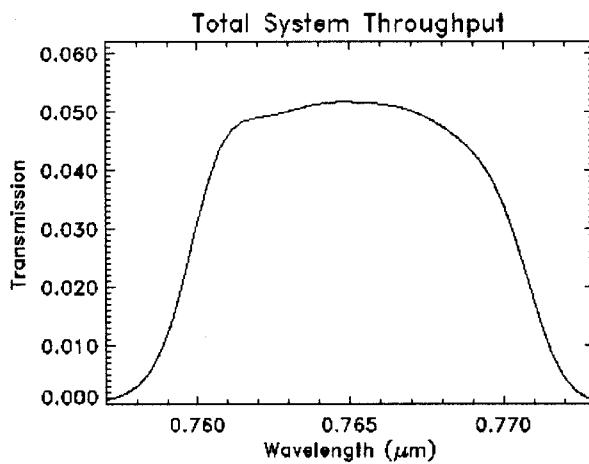
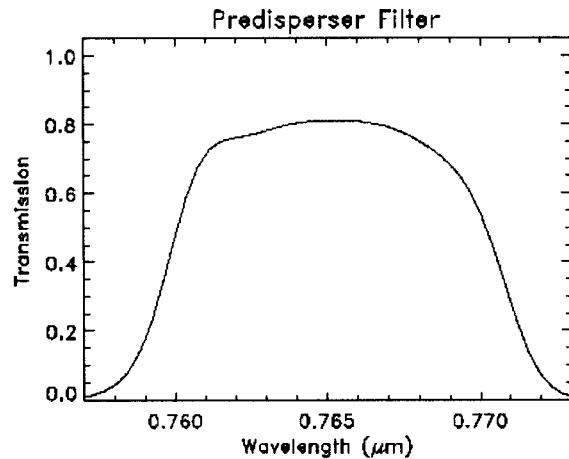
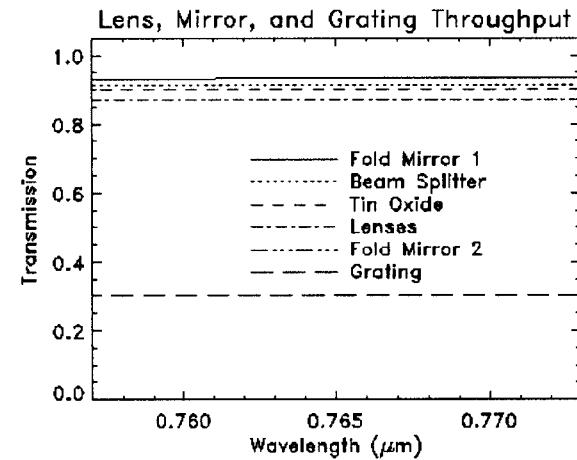
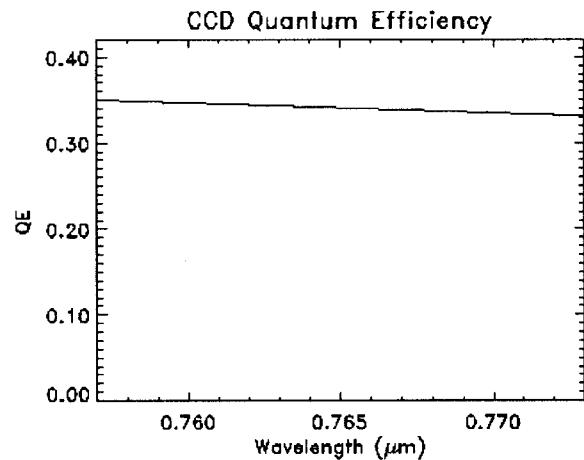


# Spectrometer Modeling Approach

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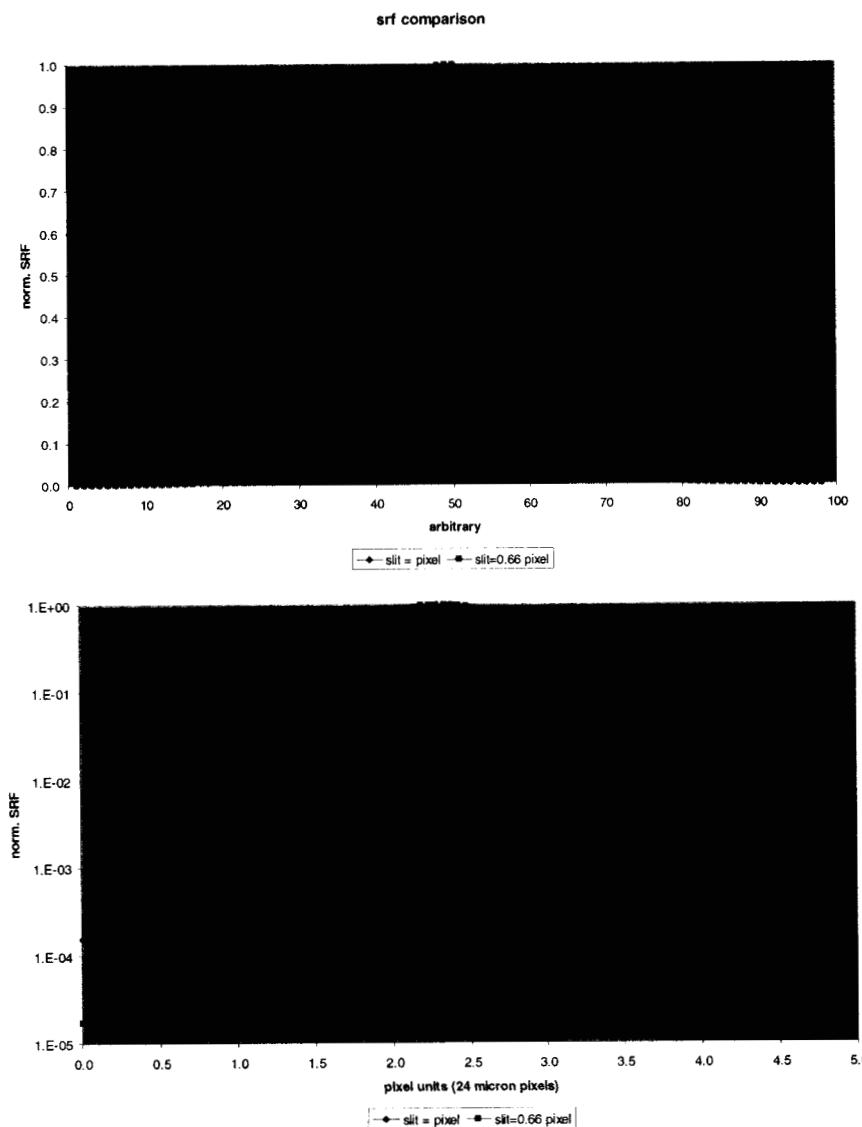
- Spectrally-dependent synthetic Radiances generated for
  - realistic clear and cloudy skies, with uniformly mixed aerosols ( $\tau_a=0.1$ )
  - solar zenith angles varying from 0 to 85 degrees
- Synthetic Spectra convolved with a realistic PABSI spectrometer slit function
- The spectrally-dependent throughput is computed assuming:
  - 2 fold mirrors (gold coated)
  - Solar channel beam splitter modeled as 5mm thick, uncoated BK7
  - Predisperser Filter: Dual, 4-cavity interference filter (peak transmittance of 0.8)
  - Indium-Tin-oxide coating (faraday cage) with transmittance of 0.9
  - Telescope assumed to be a 120mm F/2
  - 16 vacuum glass interfaces, each with 2-layer, 99% transmitting AR coatings
    - lenses and depolarizer
  - slit assumed to be 0.01 mm wide and 1.7 mm long
  - grating efficiency assumed to be 30% across the band
  - Resolving power assumed to be 26,000 (~0.03nm FWHM)
  - Exposure time of 140 ms (1 km by 1 km IFOV)
  - CCD QE near 0.33 near 760 nm (average of WFPC2 and Cassini CCD's)
    - serial spurious noise, pre-amp noise, thermal noise, and photon noise included

# System Throughput Assumptions



Wavelength-dependent values assumed for CCD Quantum Efficiency (QE), Optical system throughput, and predisisperser filter are shown as well as the total system throughput (~5%).

# Spectrometer Slit Function



- PABSI Slit Function

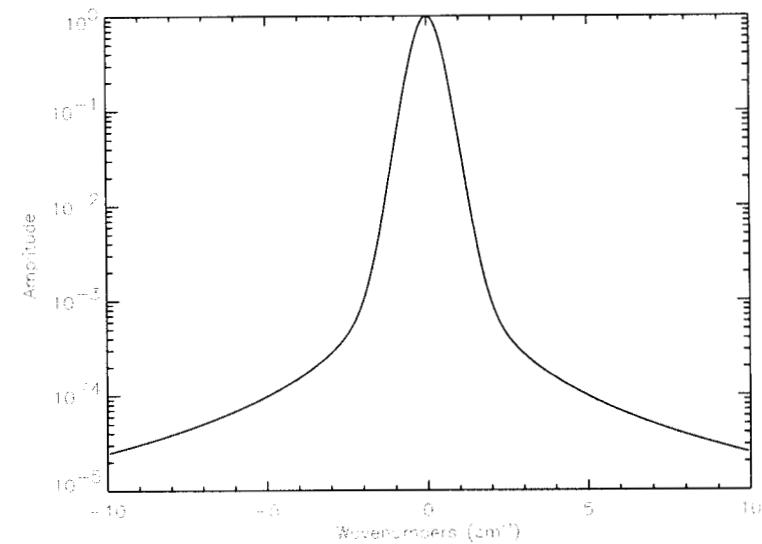
- Defined using optical software
- Simulated by a series of Lorentzians
  - Allows addition of arbitrary amounts of scattered light

$$F(v-v_0) = a L(\alpha_L, v-v_0) + b [ \gamma L(\alpha_L, v-v_0) ]^\gamma$$

where

$$L(\alpha_L, v-v_0) = \alpha_L / [\pi \{ (v-v_0)^2 + \alpha_L^2 \}]$$

$$a = 0.01, b = 0.99, \gamma = 6$$

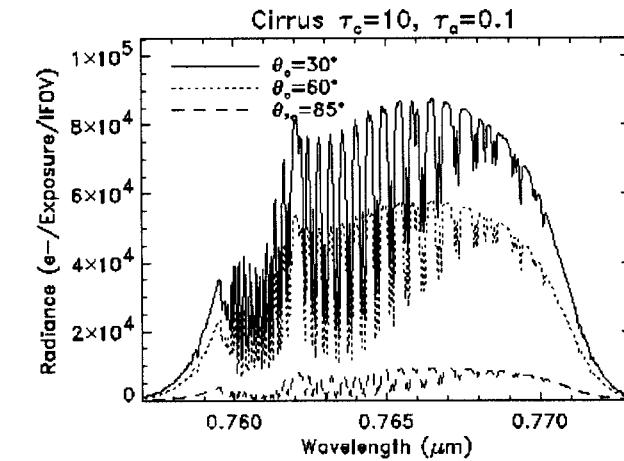
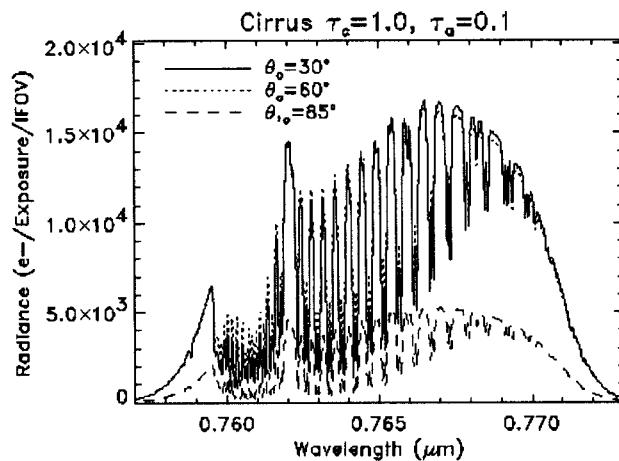
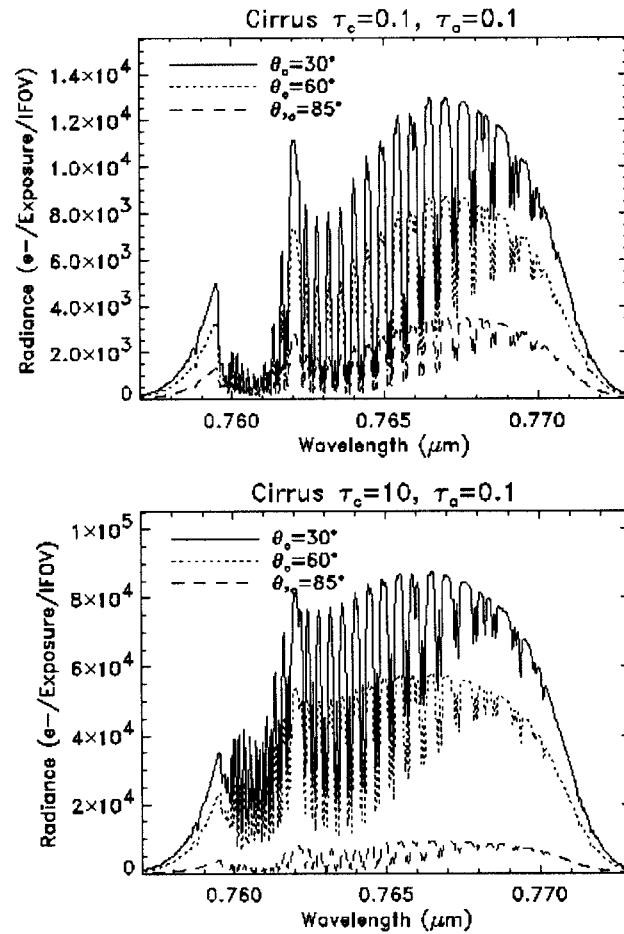
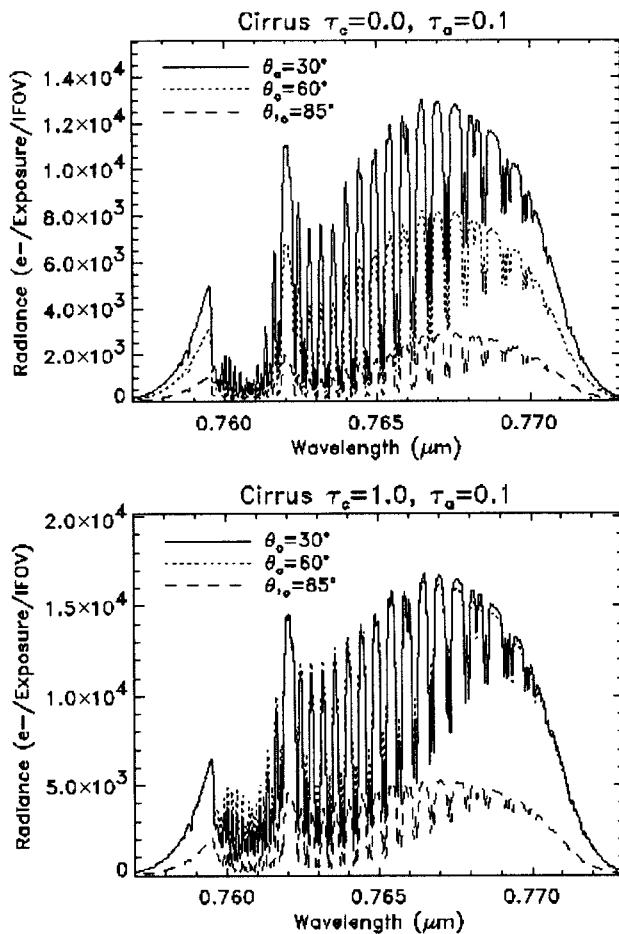


# Raw Signal Levels and S/N

Signal levels and S/N values were derived for a variety of clear and cloudy Mid Latitude Summer model atmospheres

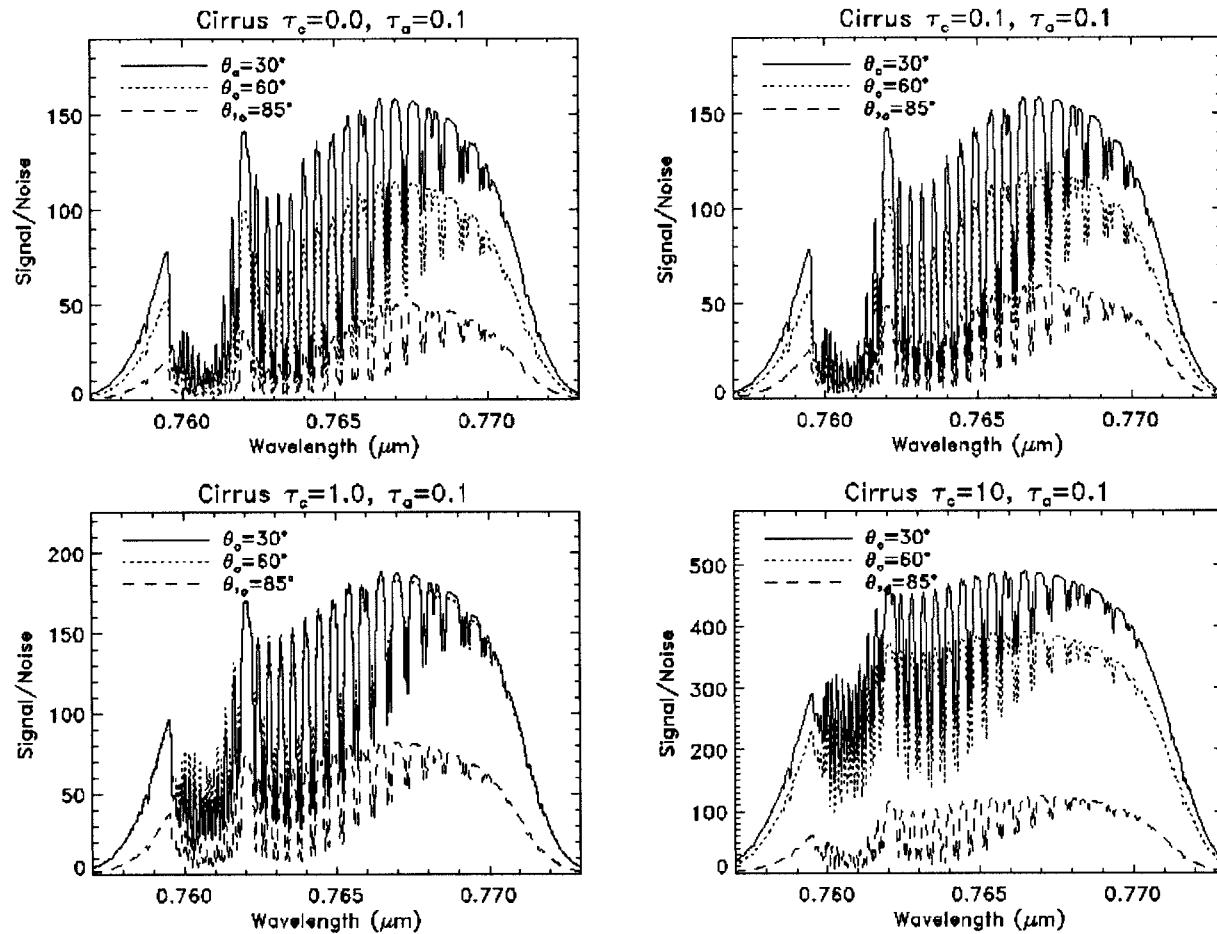
- All atmospheres included uniformly mixed tropospheric aerosols
  - Column-integrated aerosol optical depth:  $\tau_a(760\text{nm}) = 0.1$
  - Single scattering albedo,  $\omega_o(760\text{nm}) \sim 0.9$
- Solar zenith angles varying from 30 to  $85^0$
- Cloud-free conditions
- Cirrus (ice) Cloud (8.5 to 10 km, 275 to 350 mbar)
  - Optical depths:  $\tau_c(760\text{nm}) = 0.1, 1.0, 10.0$
- Alto-Stratus Cloud (4 to 4.8 km, 560 to 630 mbar)
  - Optical depths:  $\tau_c(760\text{nm}) = 0.1, 1.0, 10.0$
- Strato-Cumulus Clouds (1 to 1.5 km, ~830 to 870 mbar)
  - Optical depths:  $\tau_c(760\text{nm}) = 0.1, 1.0, 10.0$
- Notes:
  - Exposure levels expressed in detector units (electrons/exposure/IFOV)
  - Noise estimates include read noise, thermal noise, and photon noise
  - Shape of continuum determined primarily by predisperser filter

# Exposure Level for Cirrus Clouds



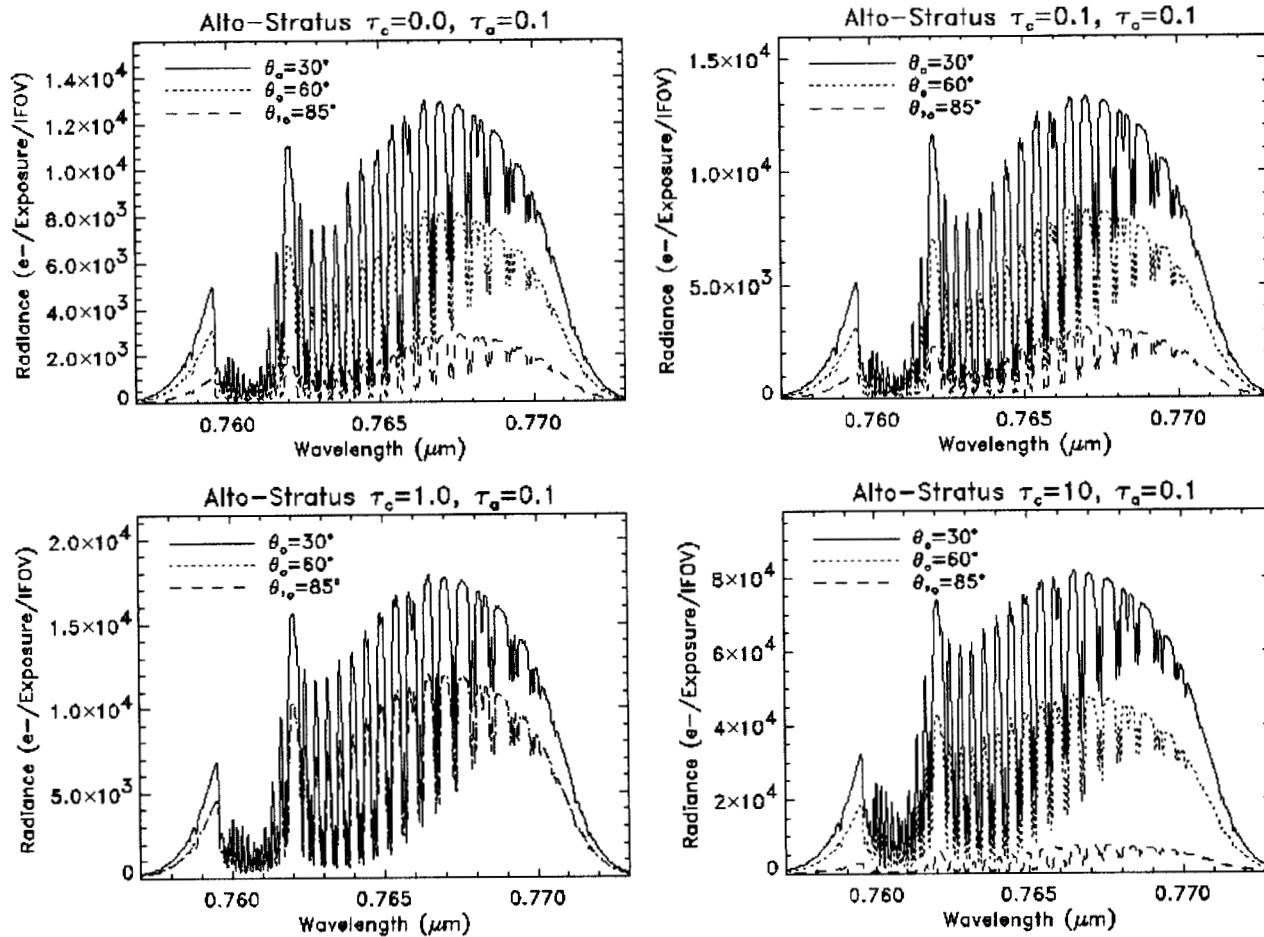
Solar Zenith Angle,  $\theta_o$ , Cloud Optical Depth,  $\tau_c$ , Aerosol Optical Depth,  $\tau_a$

# S/N for Cirrus Clouds



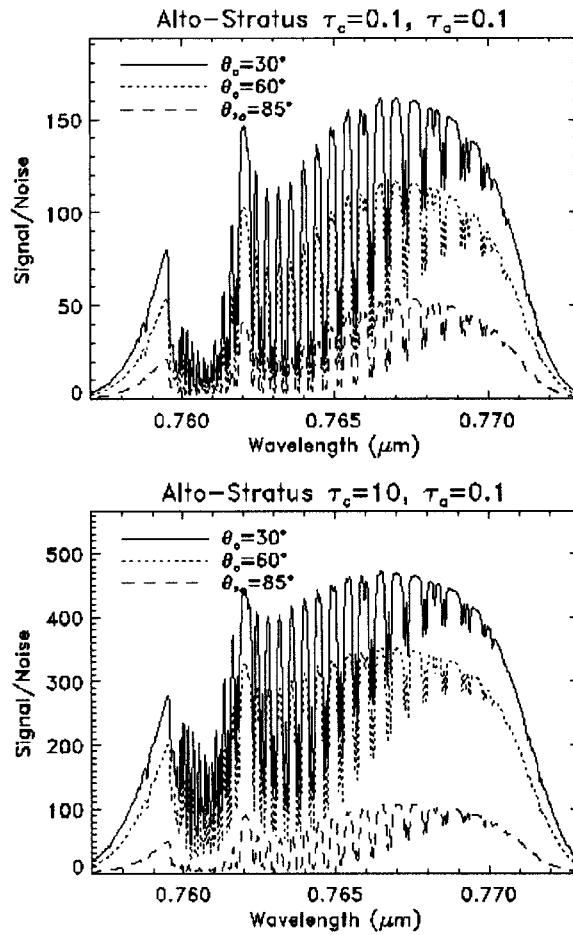
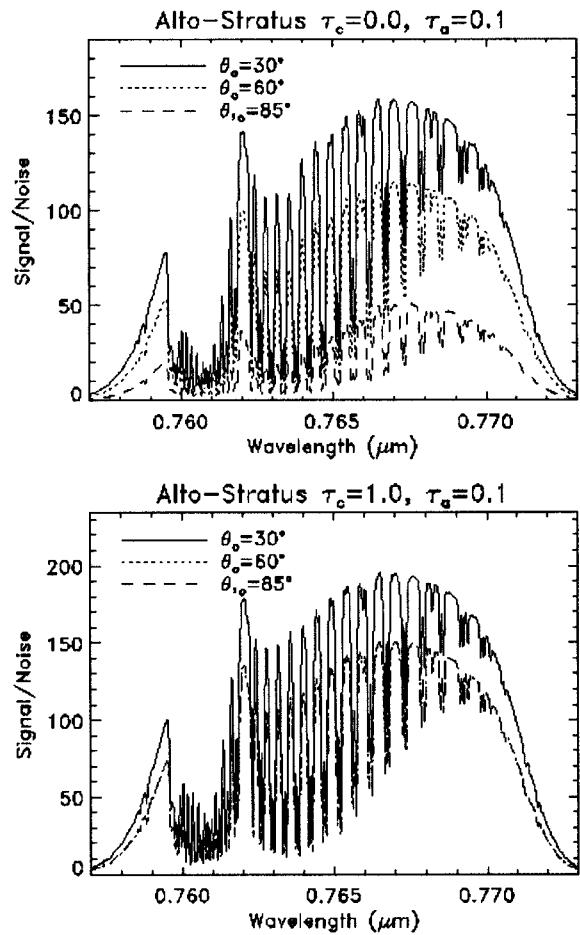
Solar Zenith Angle,  $\theta_o$ , Cloud Optical Depth,  $\tau_c$ , Aerosol Optical Depth,  $\tau_a$

# Exposure Level for Alto Stratus Clouds



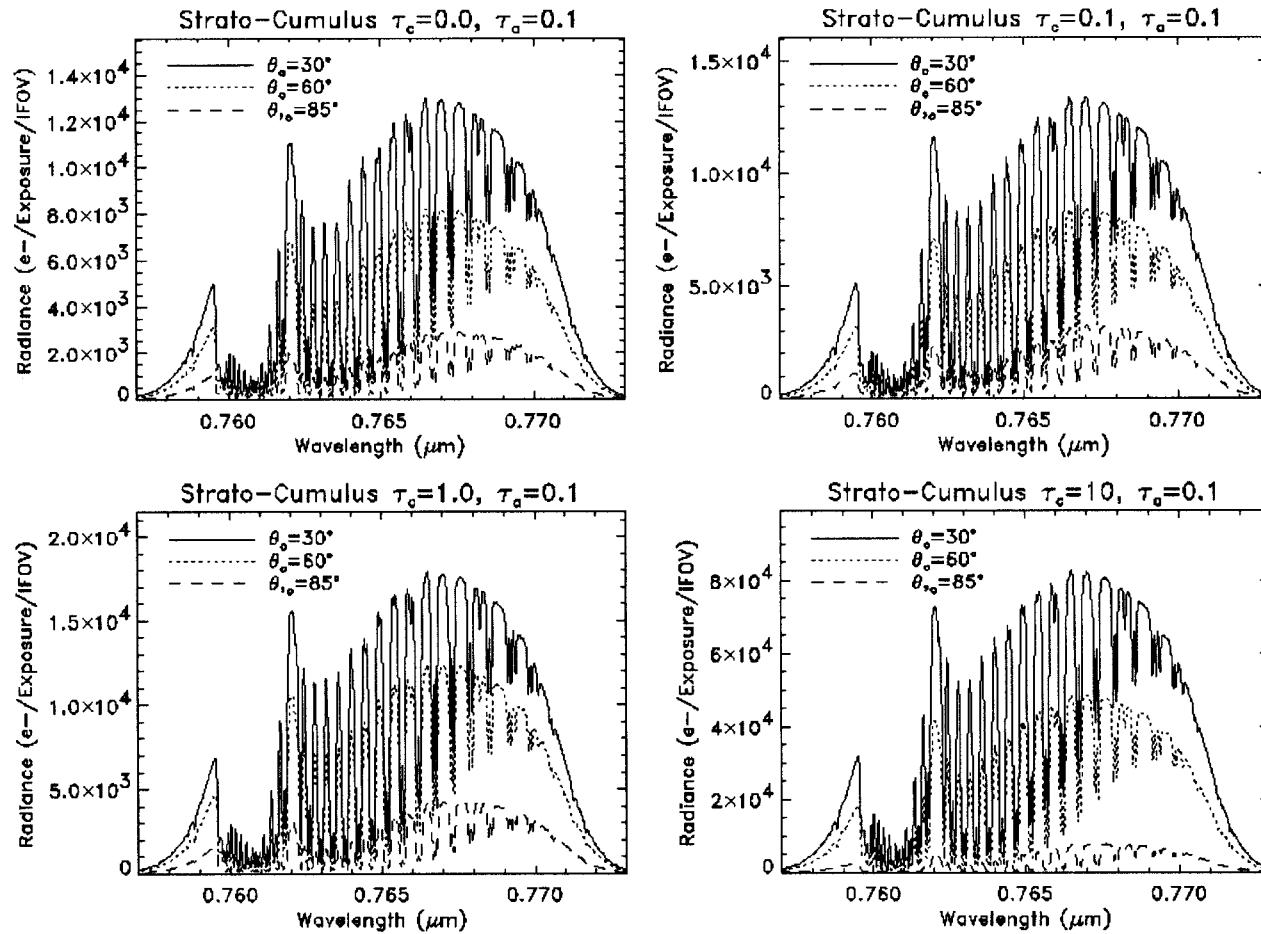
Solar Zenith Angle,  $\theta_o$ , Cloud Optical Depth,  $\tau_c$ , Aerosol Optical Depth,  $\tau_a$

# S/N for Alto-Stratus Clouds



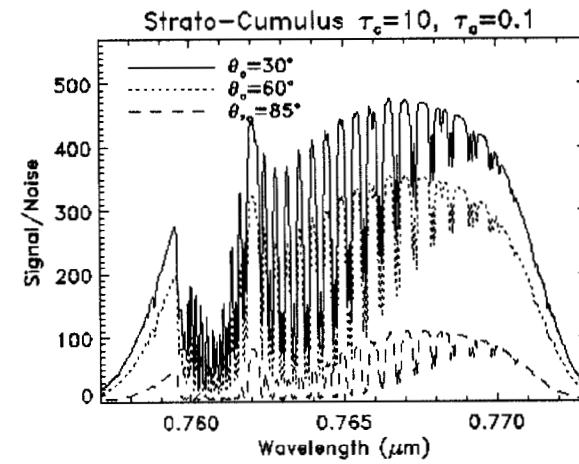
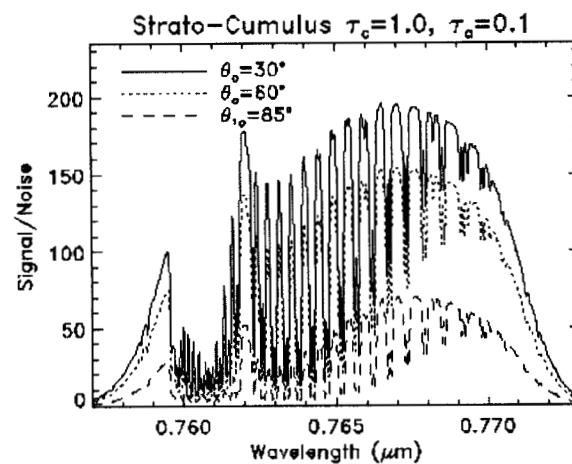
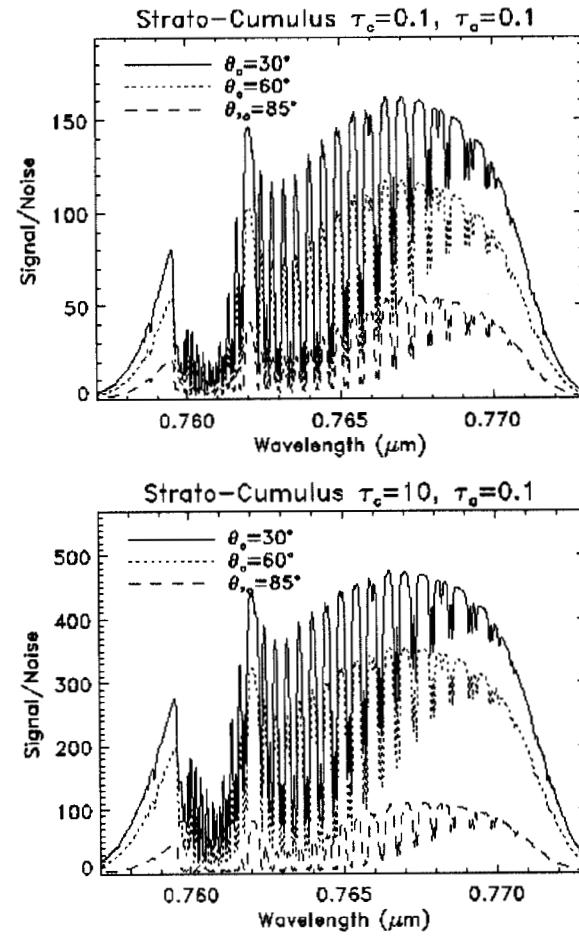
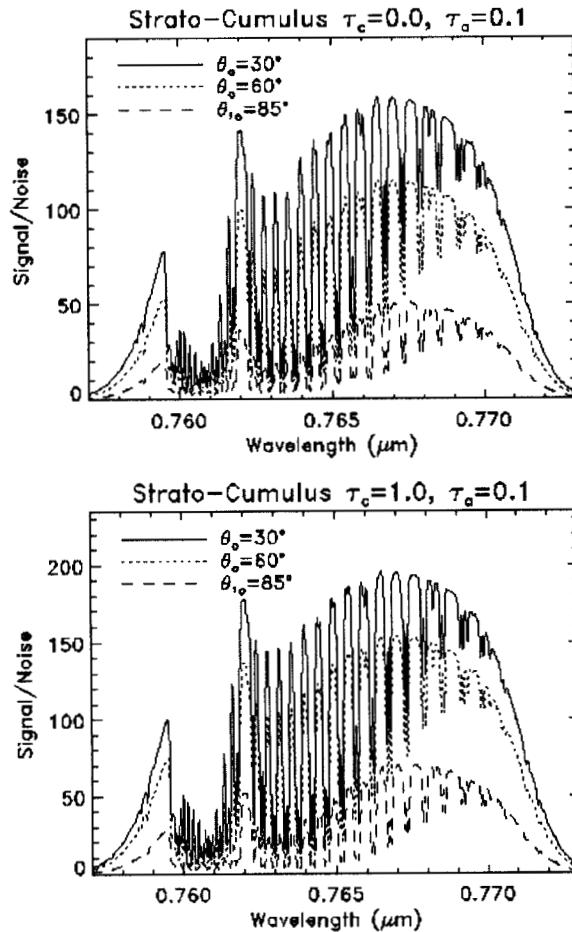
Solar Zenith Angle,  $\theta_o$ , Cloud Optical Depth,  $\tau_c$ , Aerosol Optical Depth,  $\tau_a$

# Exposure Level for Strato-Cumulus Clouds



Solar Zenith Angle,  $\theta_o$ , Cloud Optical Depth,  $\tau_c$ , Aerosol Optical Depth,  $\tau_a$

# S/N for Strato-Cumulus Clouds



Solar Zenith Angle,  $\theta_0$ , Cloud Optical Depth,  $\tau_c$ , Aerosol Optical Depth,  $\tau_a$



# Conclusions about Raw S/N

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- Clear, aerosol-laden conditions yield S/N values
  - <50 for solar zenith angles greater than 85°
  - >150 for solar zenith angles near 30°
- Thin clouds ( $\tau_c = 1.0$ ;  $\tau_a=0.1$ ) yield S/N values
  - ~60 for zenith angles >85°
  - ~200 for solar zenith angles near 30°
- Thick clouds ( $\tau_c = 10$ ;  $\tau_a=0.1$ ) yield S/N values
  - ~100 for zenith angles >85°
  - ~450 for solar zenith angles near 30°



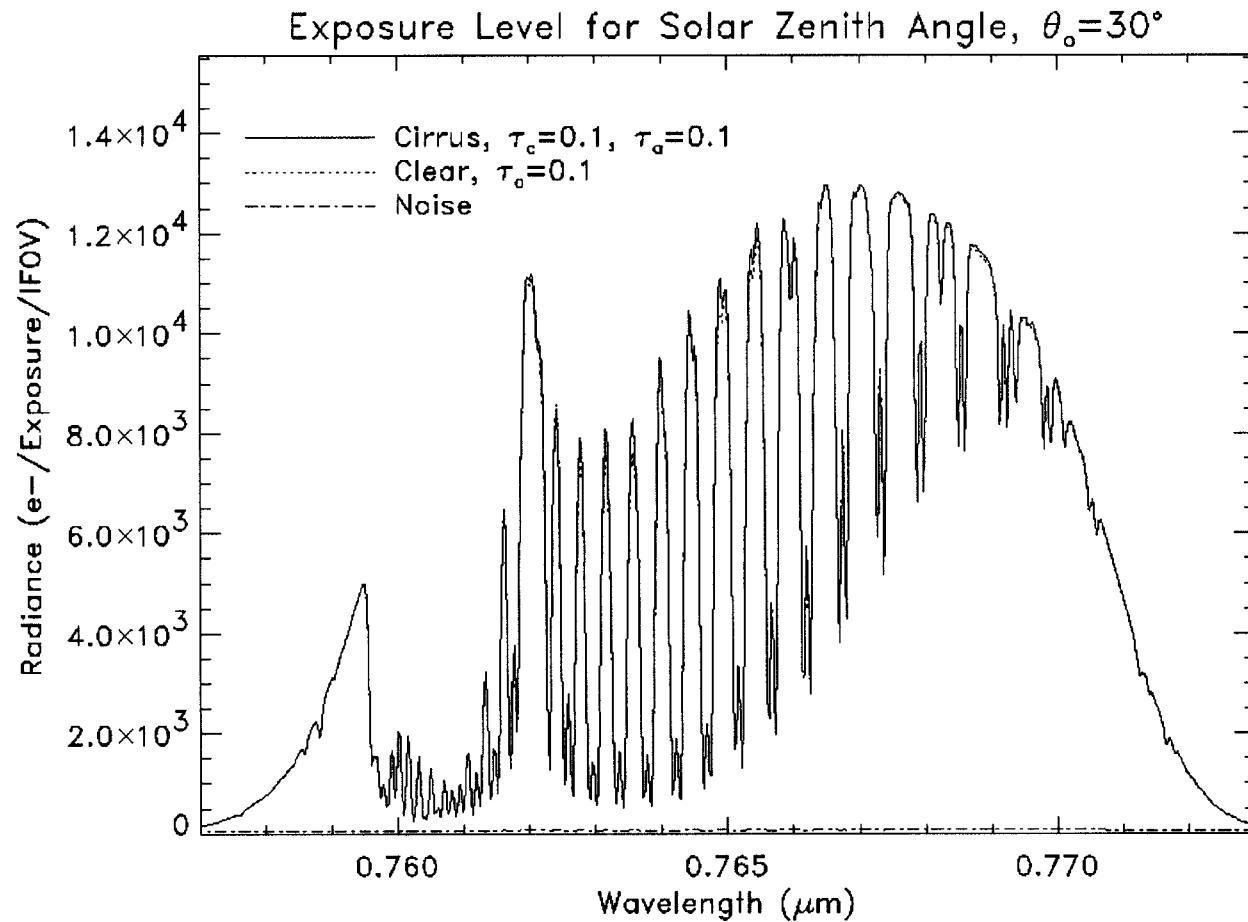
These results meet all of PABSI's formal S/N requirements

# Sensitivities to Thin Clouds

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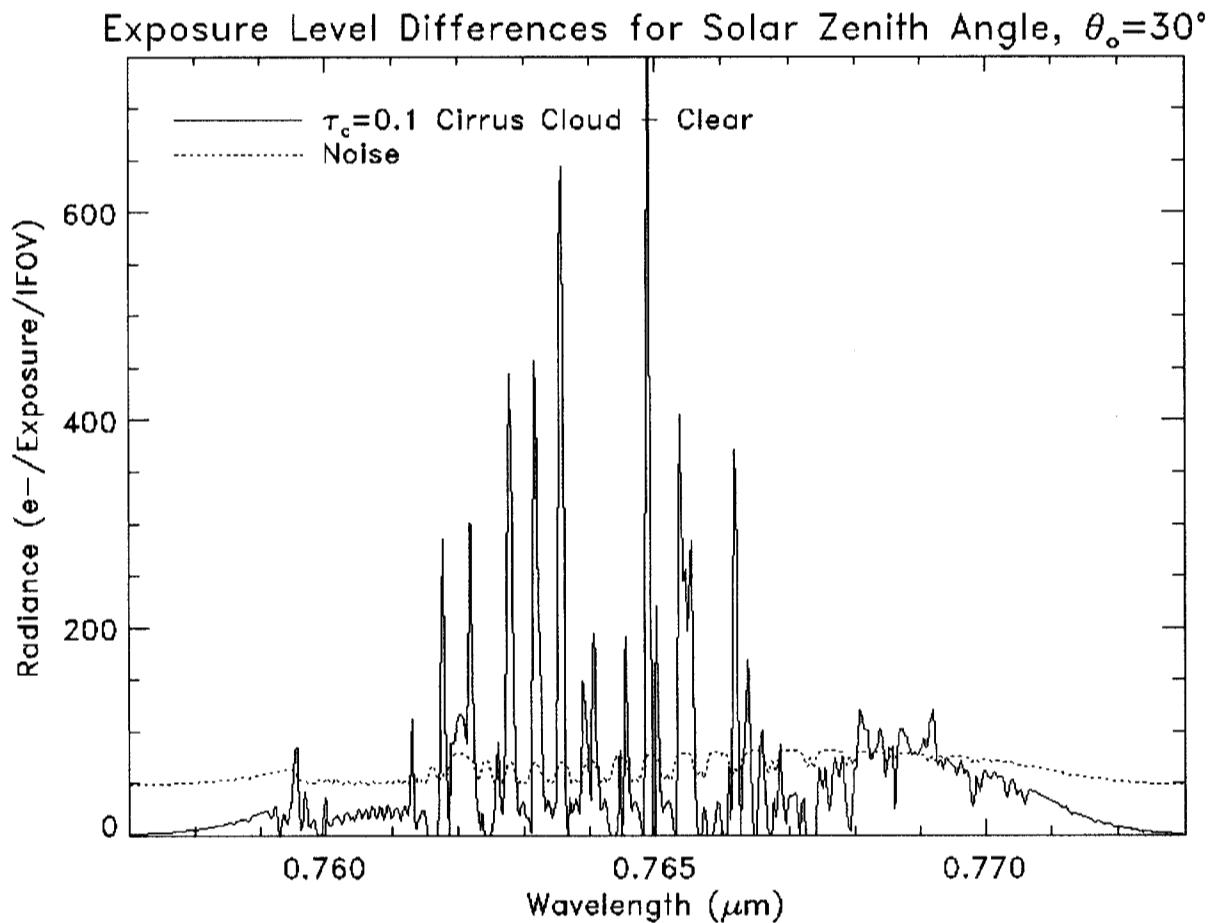
- Even though PABSI meets its formal S/N requirements additional tests were required to insure that this design can detect and discriminate
  - Thin ( $\tau_c = 0.1$ ), high, ice clouds
  - Thin ( $\tau_c = 1.0$ ), low, liquid water clouds
  - Multi-Layer clouds
- A series of tests were run to determine the detection limits
  - Radiances were generated for aerosol-laden ( $\tau_a = 0.1$ ) MLS model atmospheres with and without cloud layers
  - Synthetic spectra processed with the instrument simulation software
  - Results were subtracted (Cloudy - Clear) and compared to the noise level
    - Thin ( $\tau_c = 0.1$ ) Cirrus clouds
    - Thin ( $\tau_c = 0.1$ ) Strato-Cumulus clouds
    - Moderately-thin ( $\tau_c = 1.0$ ) Strato-Cumulus clouds
    - Thin ( $\tau_c = 0.1$ ) Cirrus cloud over a thick ( $\tau_c = 10$ ) Strato-Cumulus cloud
  - Results are displayed for solar zenith angles of 30 and 85°

# Sensitivity to Thin ( $\tau=0.1$ ) Cirrus Clouds



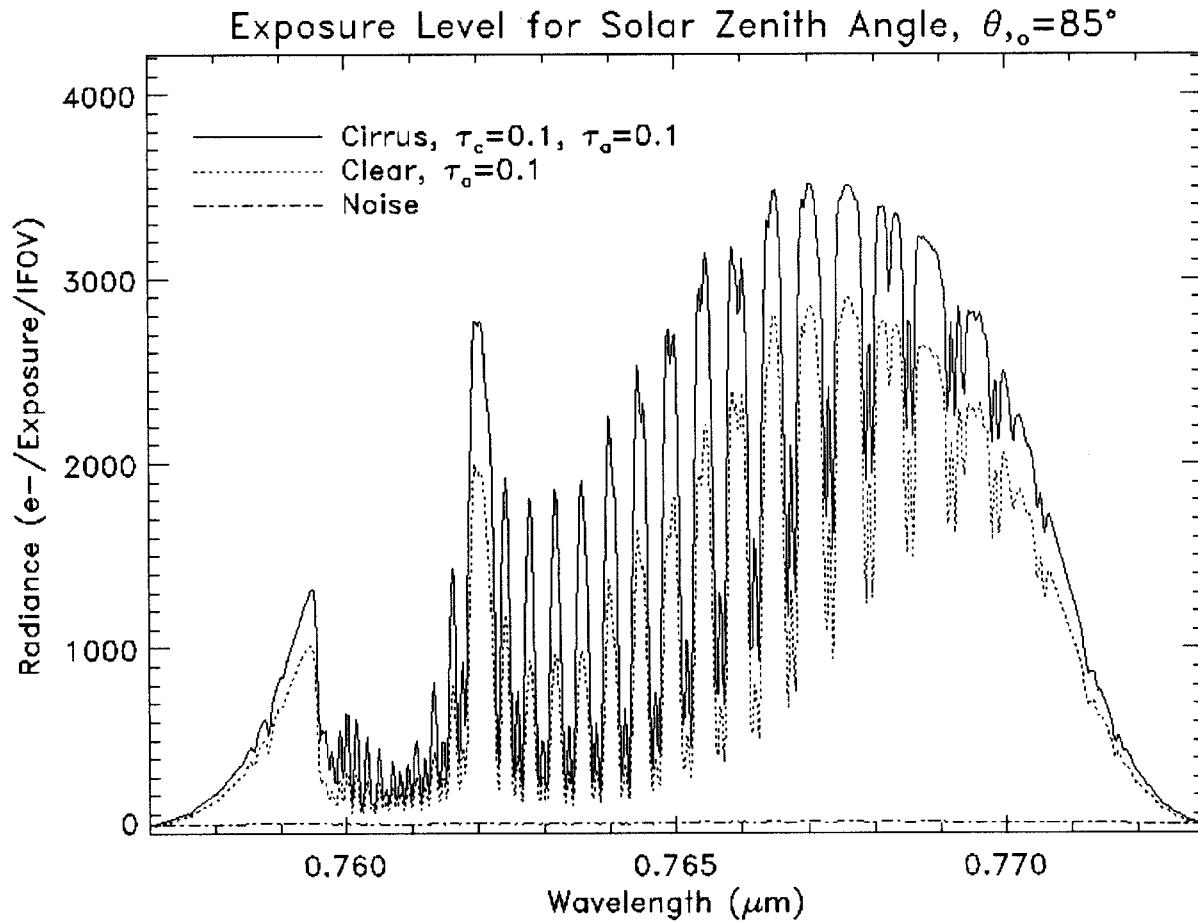
Exposure levels for cases with a thin aerosol layer ( $\tau_a=0.1$ ) and a thin ( $\tau_c=0.1$ ) cirrus cloud are compared for a solar zenith angle of  $30^\circ$

## Difference Between Clear and $\tau_c=0.1$ Case



Thin ( $\tau=0.1$ ) cirrus cloud is detected at  $\sim 12$  times the noise level at solar zenith angle of  $30^\circ$

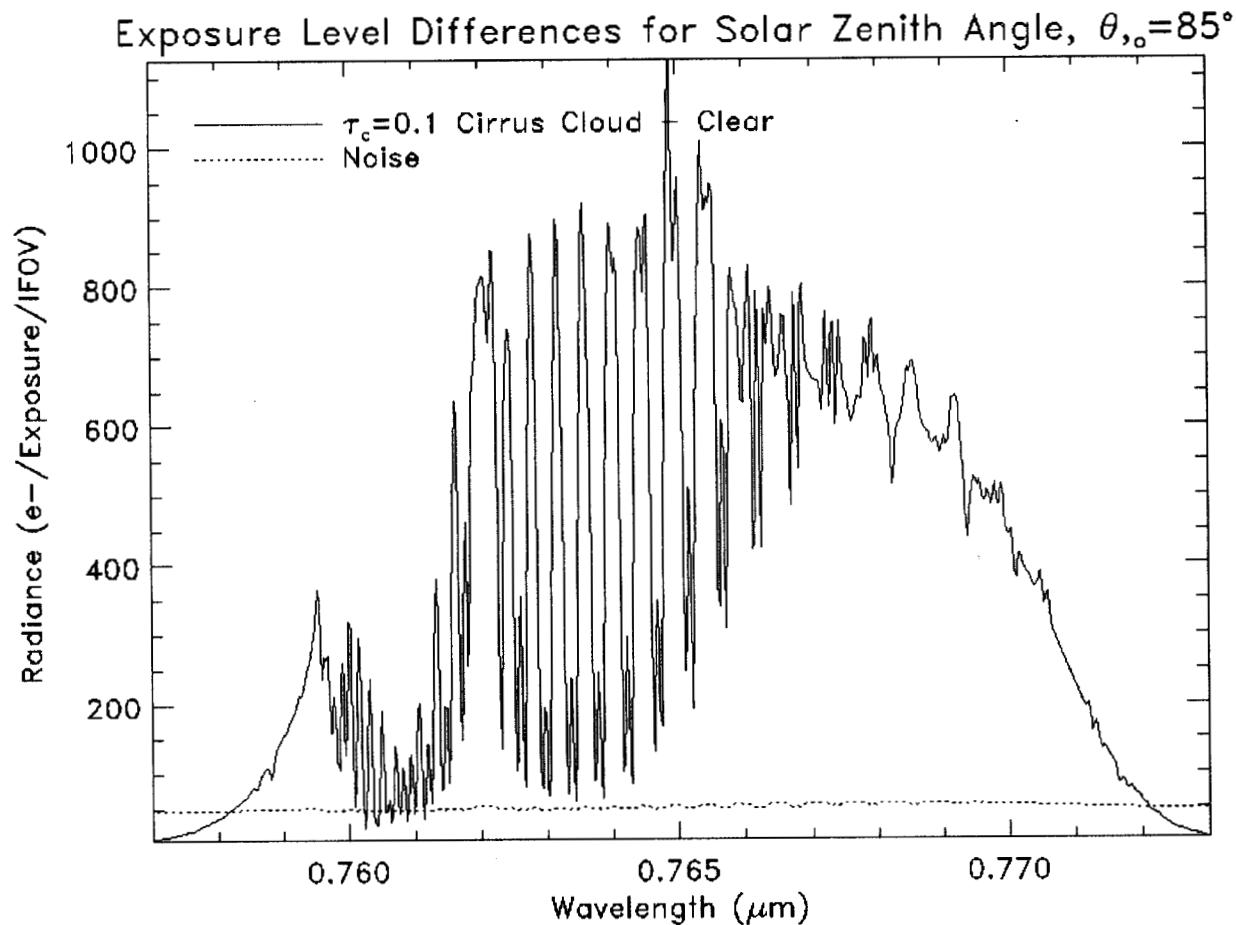
# Sensitivity to Thin ( $\tau=0.1$ ) Cirrus Clouds



Exposure levels for cases with a thin aerosol layer ( $\tau_a=0.1$ ) and a thin ( $\tau_c=0.1$ ) cirrus cloud are compared for a solar zenith angle of  $85^\circ$ .

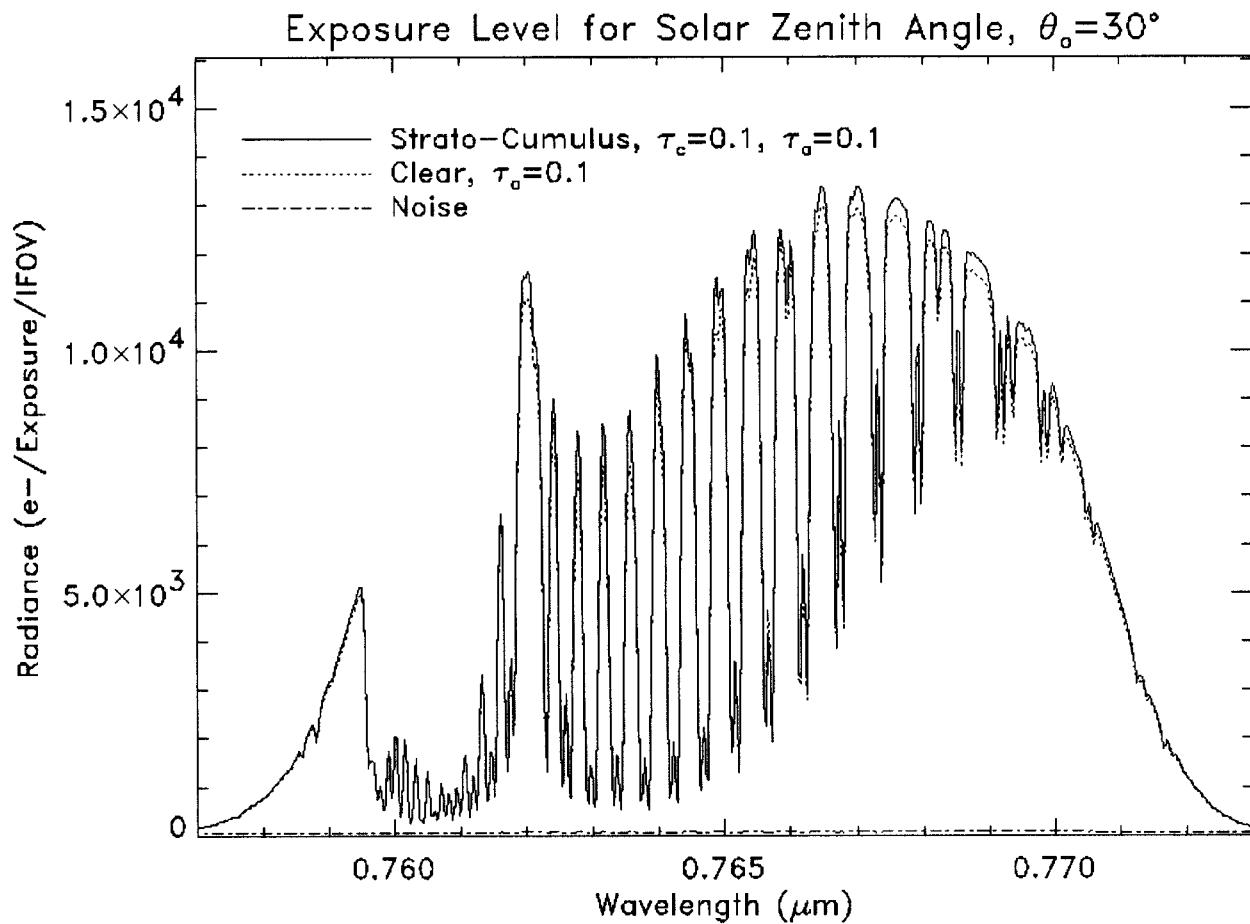


## Difference Between Clear and $\tau_c=0.1$ Case



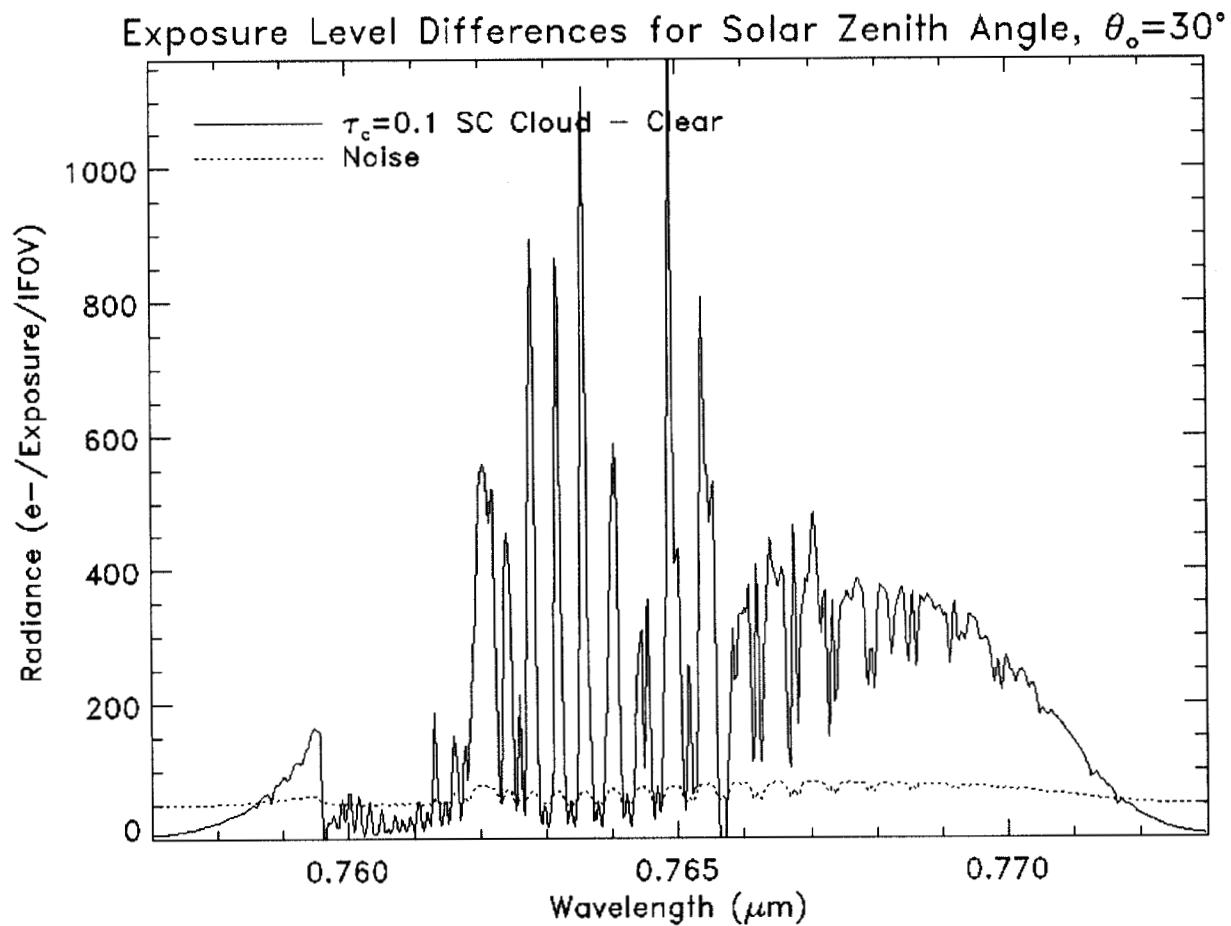
Thin ( $\tau=0.1$ ) cirrus cloud is detected at  $\sim 20$  times the noise level at solar zenith angle of  $85^\circ$

# Sensitivity to Very Thin ( $\tau=0.1$ ) Low Clouds

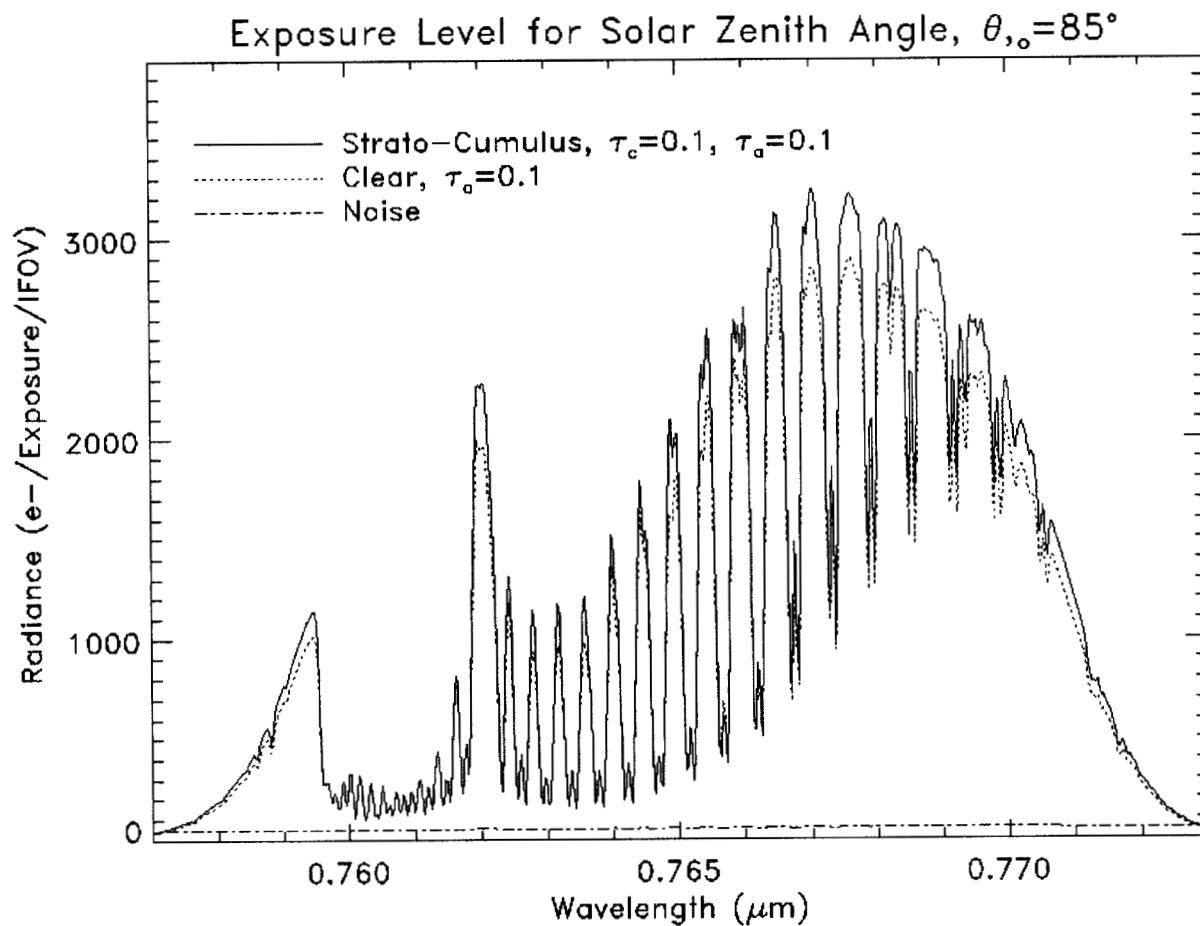




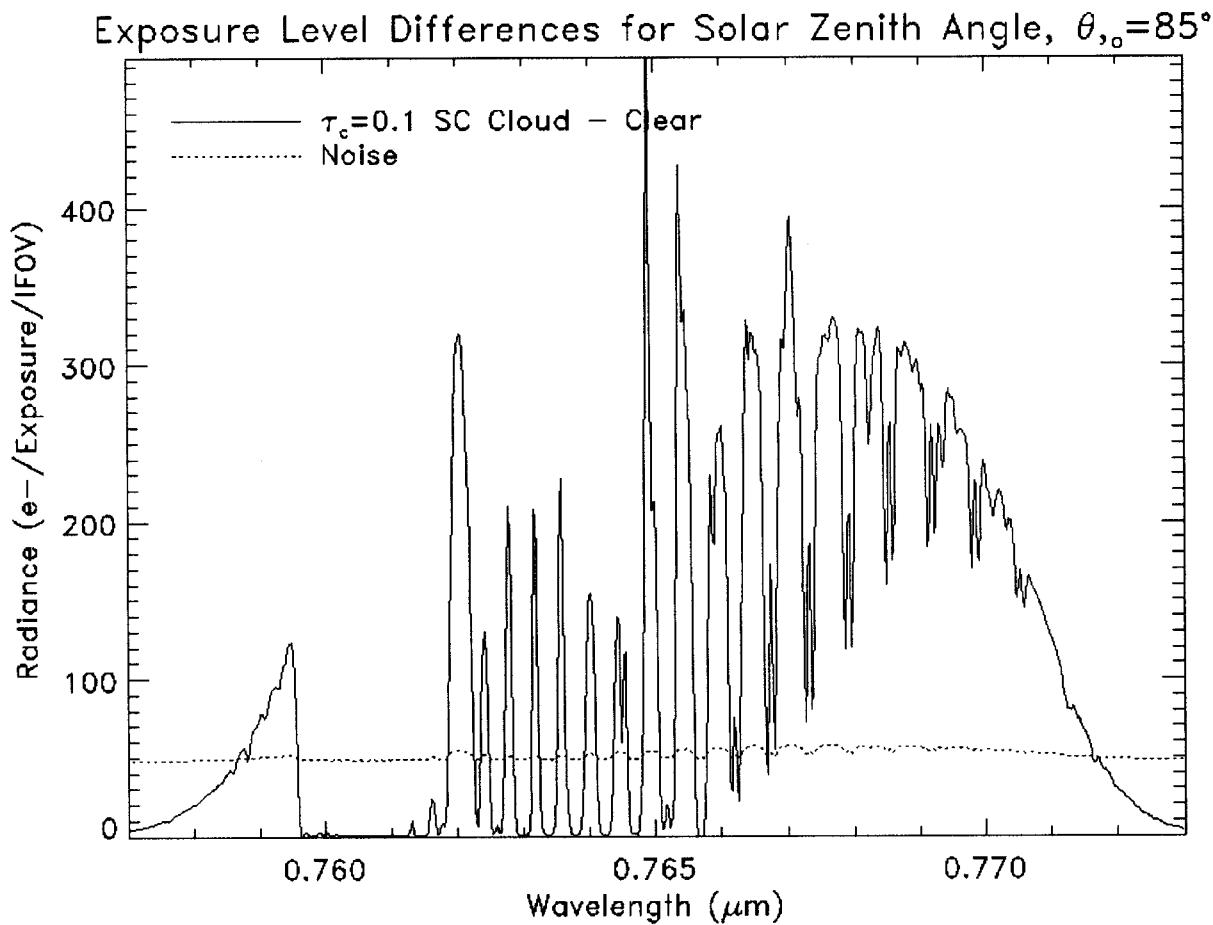
## Difference Between Clear and $\tau_c=0.1$ Case



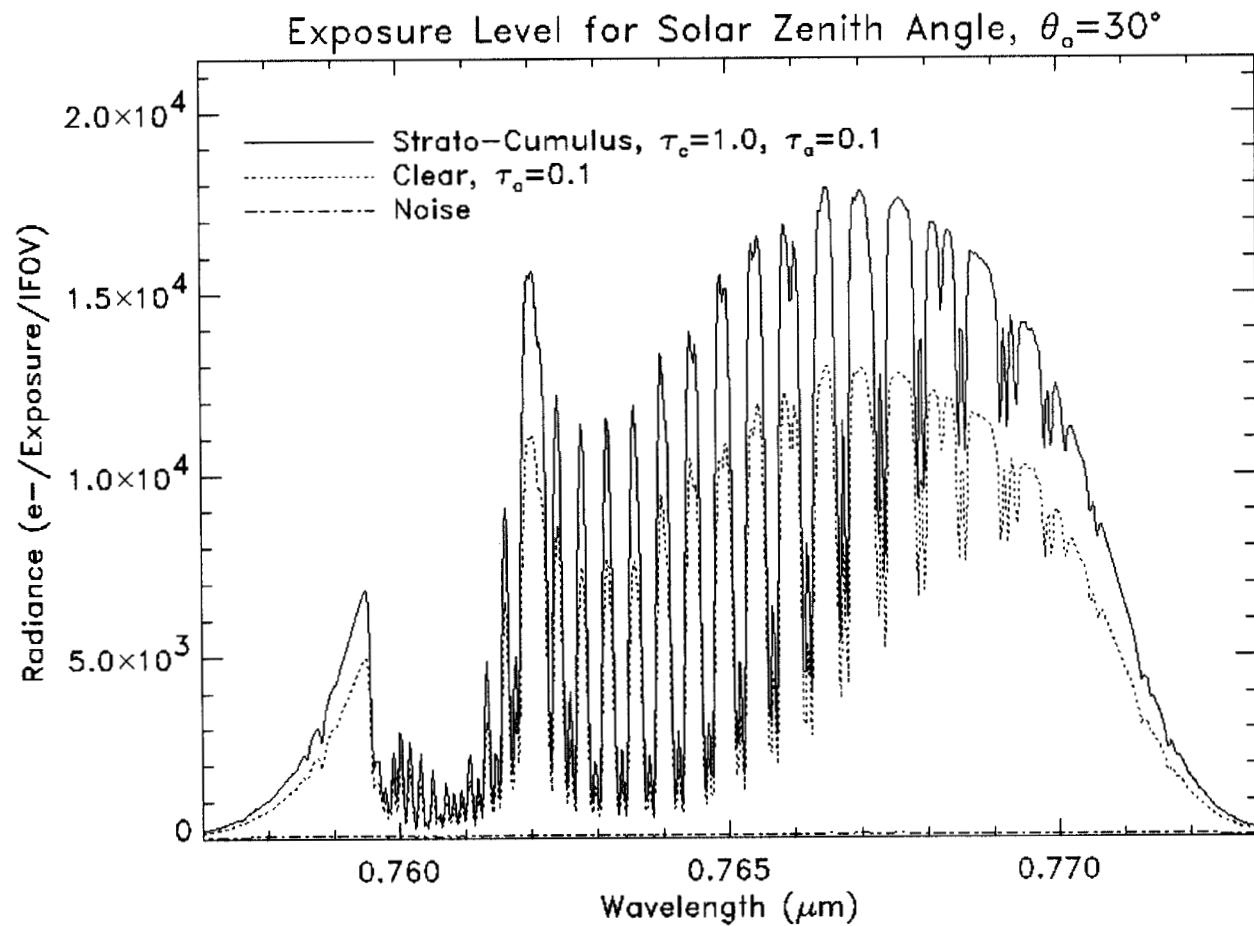
# Sensitivity to Very Thin ( $\tau=0.1$ ) Low Clouds

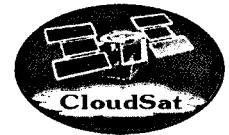


# Difference Between Clear and $\tau_c=0.1$ Case

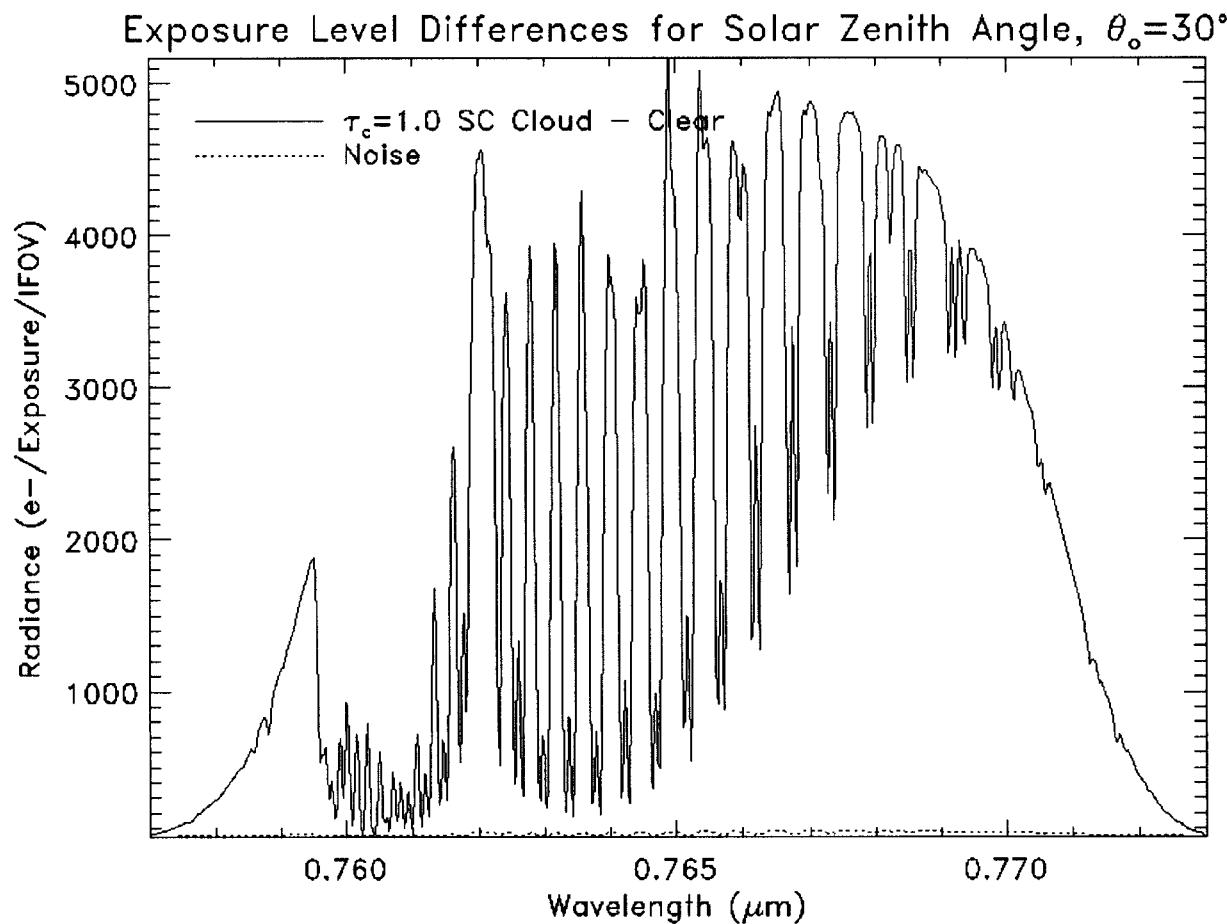


# Sensitivity to Moderately Thin ( $\tau_c=1$ ) Low Clouds

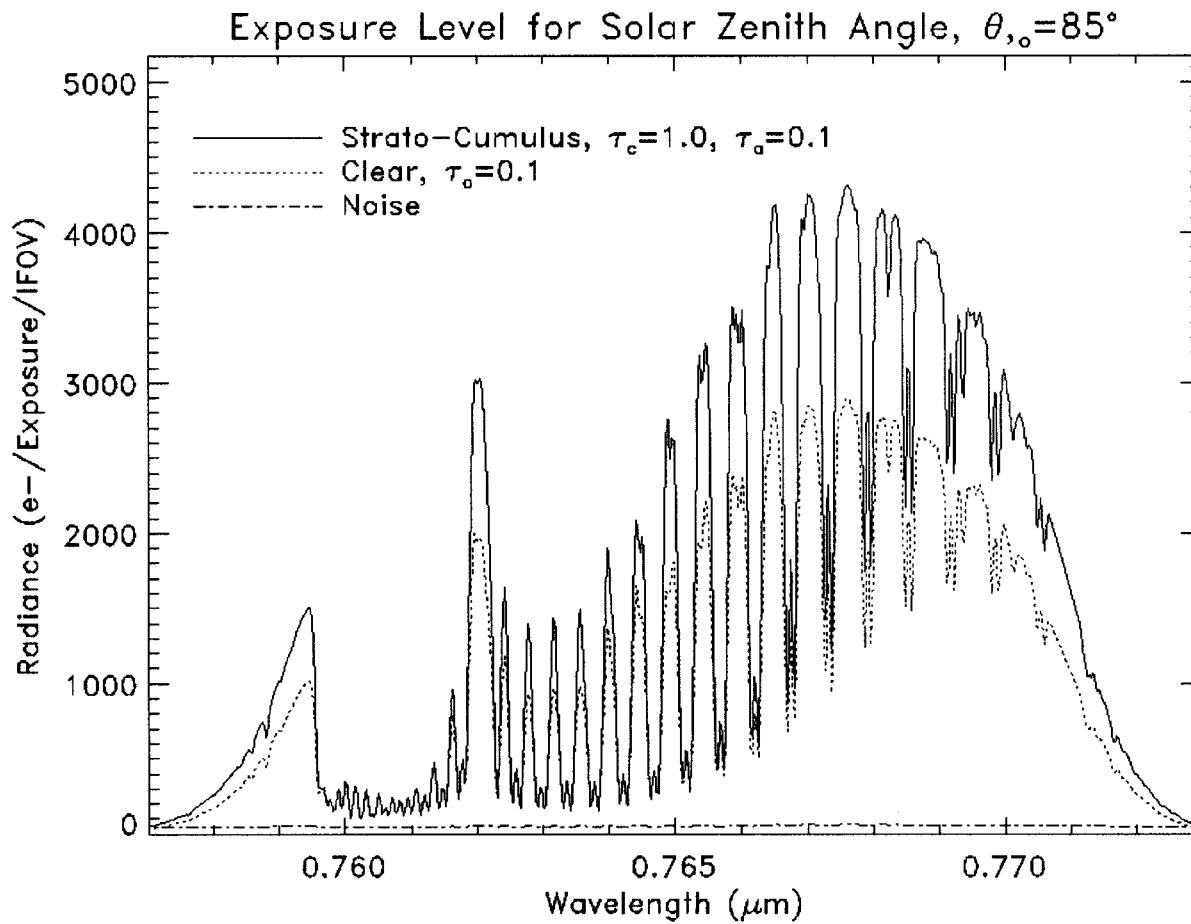




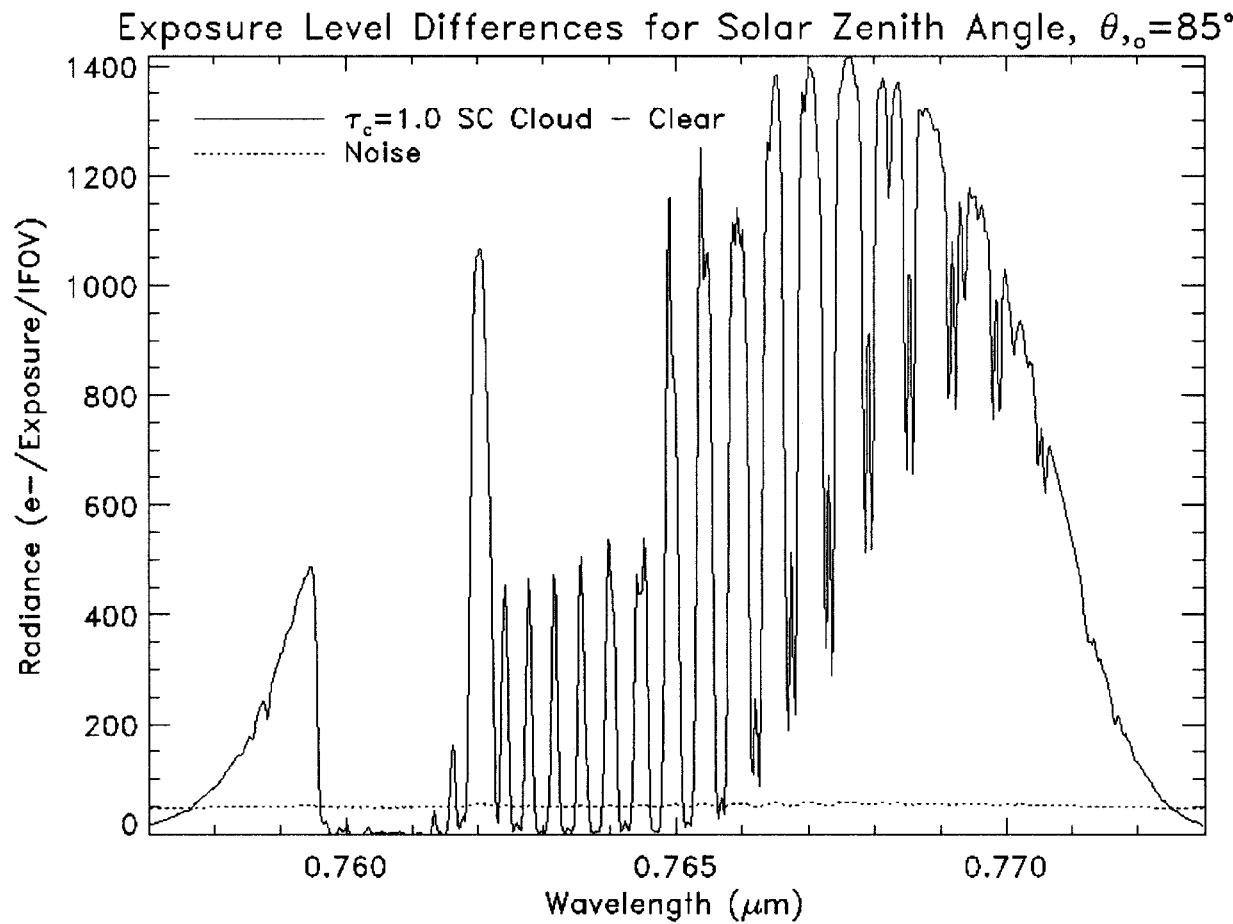
## Difference Between Clear and $\tau_c=1$ Case



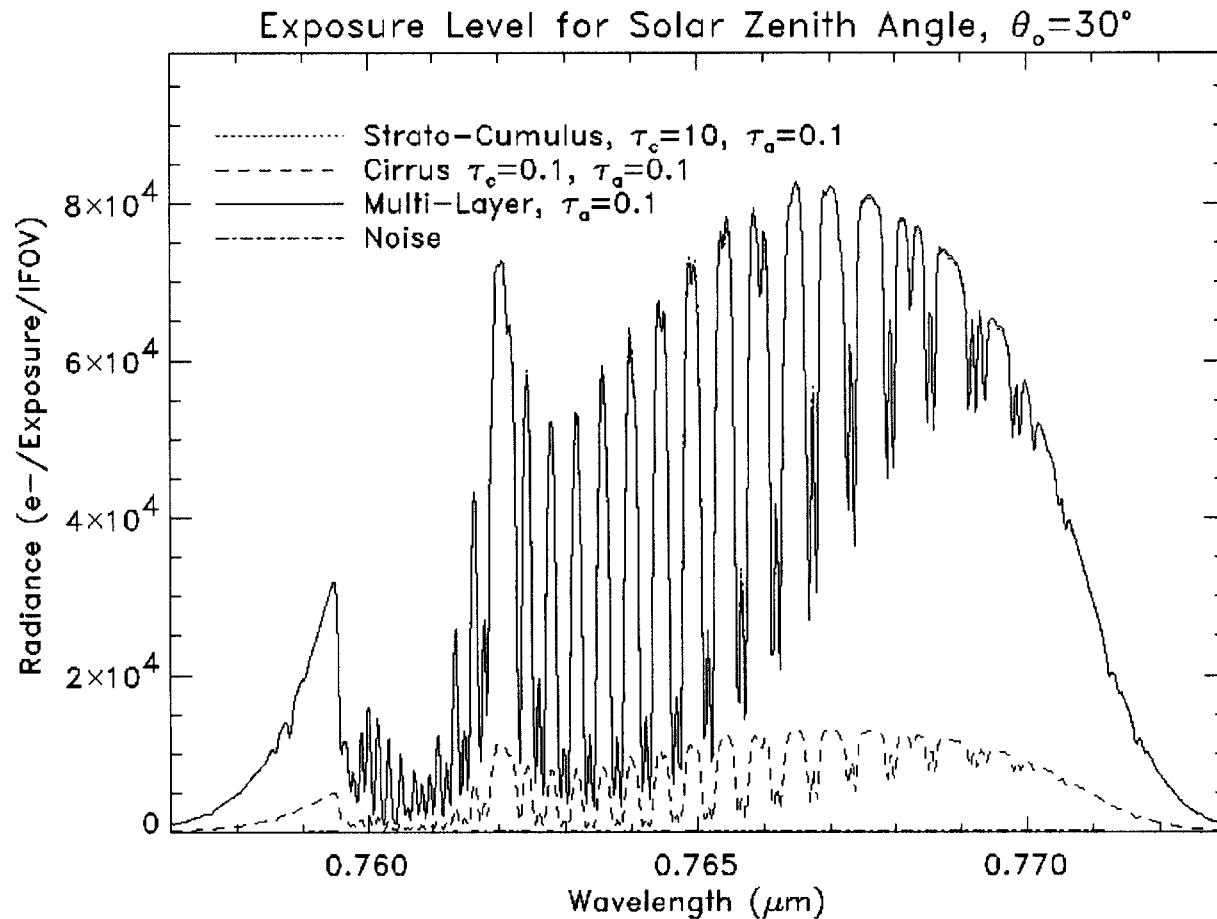
# Sensitivity to Moderately Thin ( $\tau_c=1$ ) Low Clouds



# Difference Between Clear and $\tau_c=1$ Case

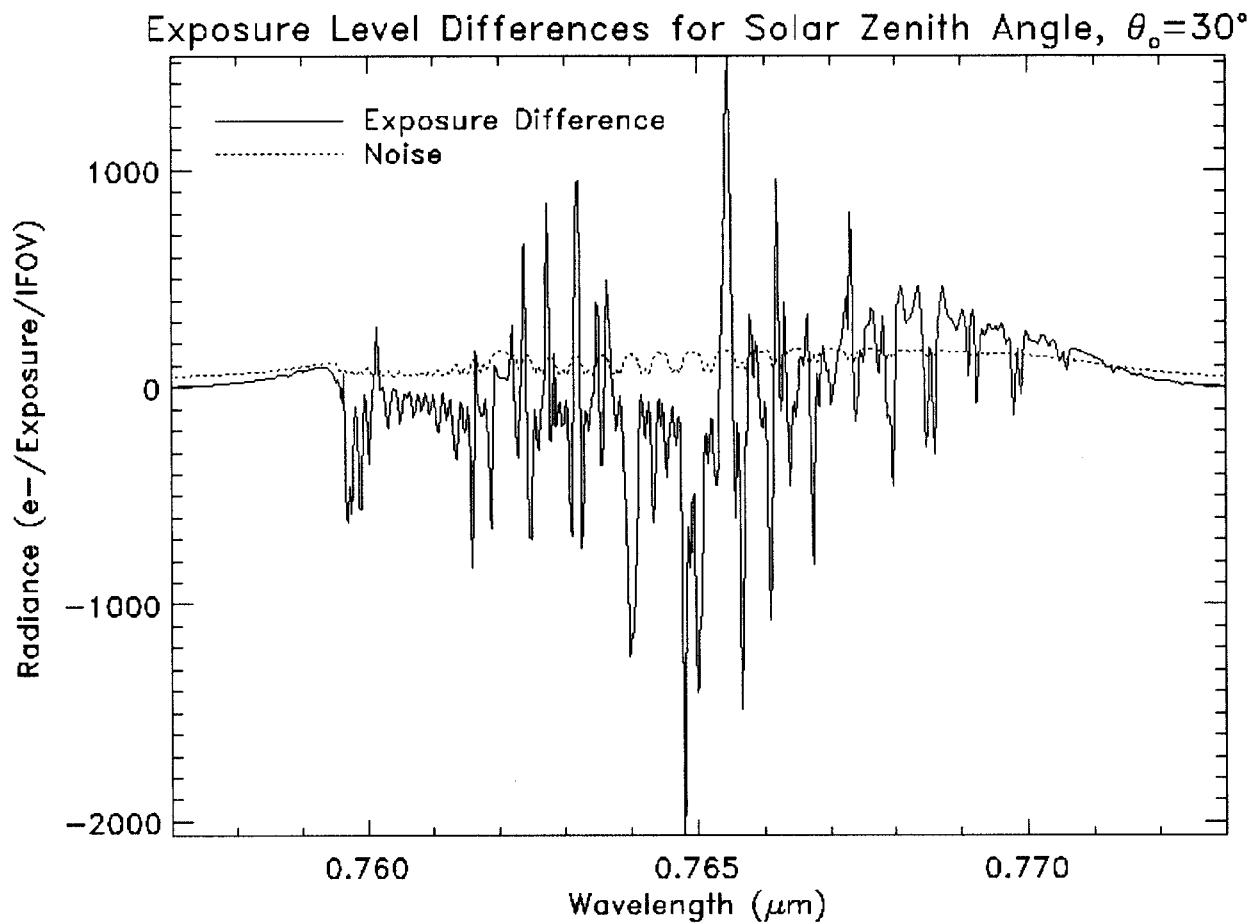


# Multi-Layer Cloud Case for High Sun

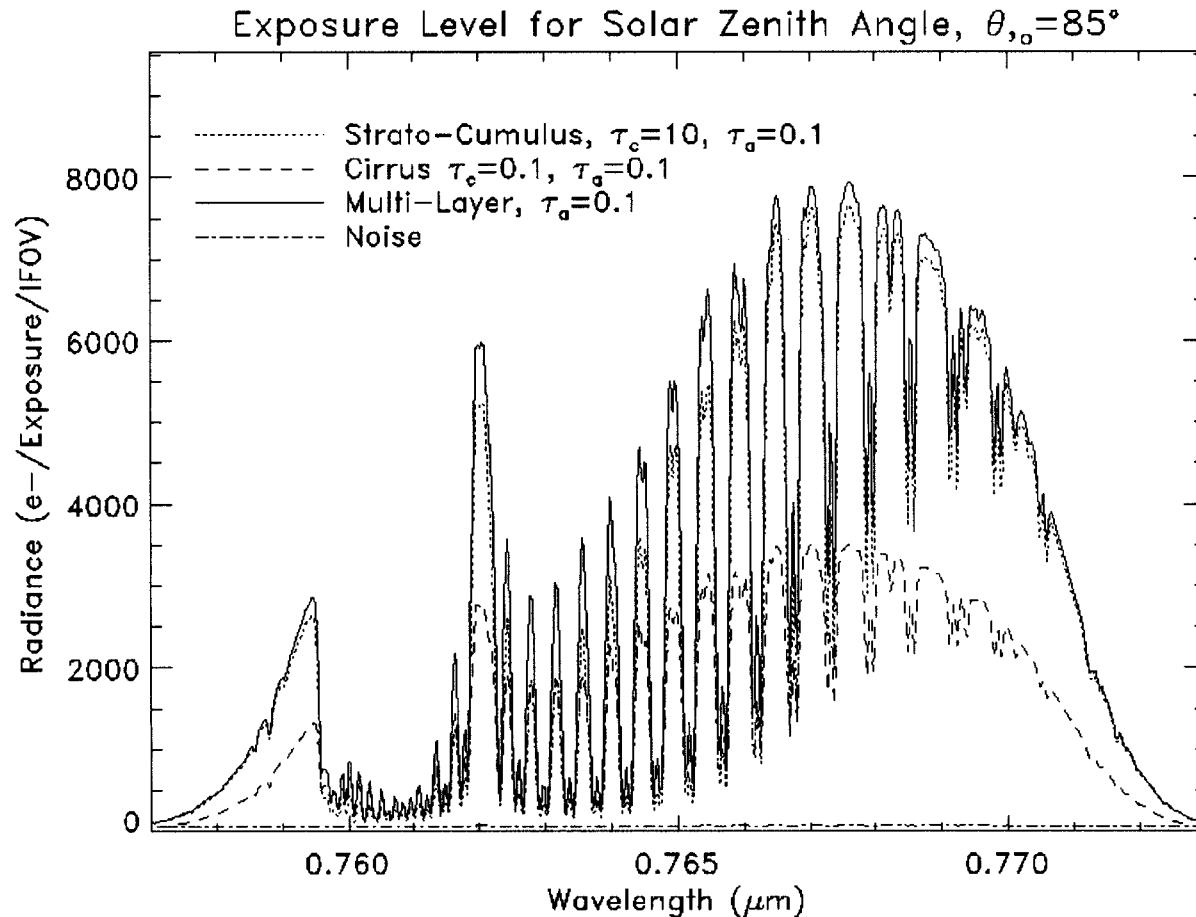


Multi-layer case includes an optically thick ( $\tau_c=10$ ) low cloud and an optically thin ( $\tau_c=0.1$ ) high cirrus cloud. All cases include a thin ( $\tau_a=0.1$ ) aerosol layer.

# Difference Produced by Cirrus Cloud

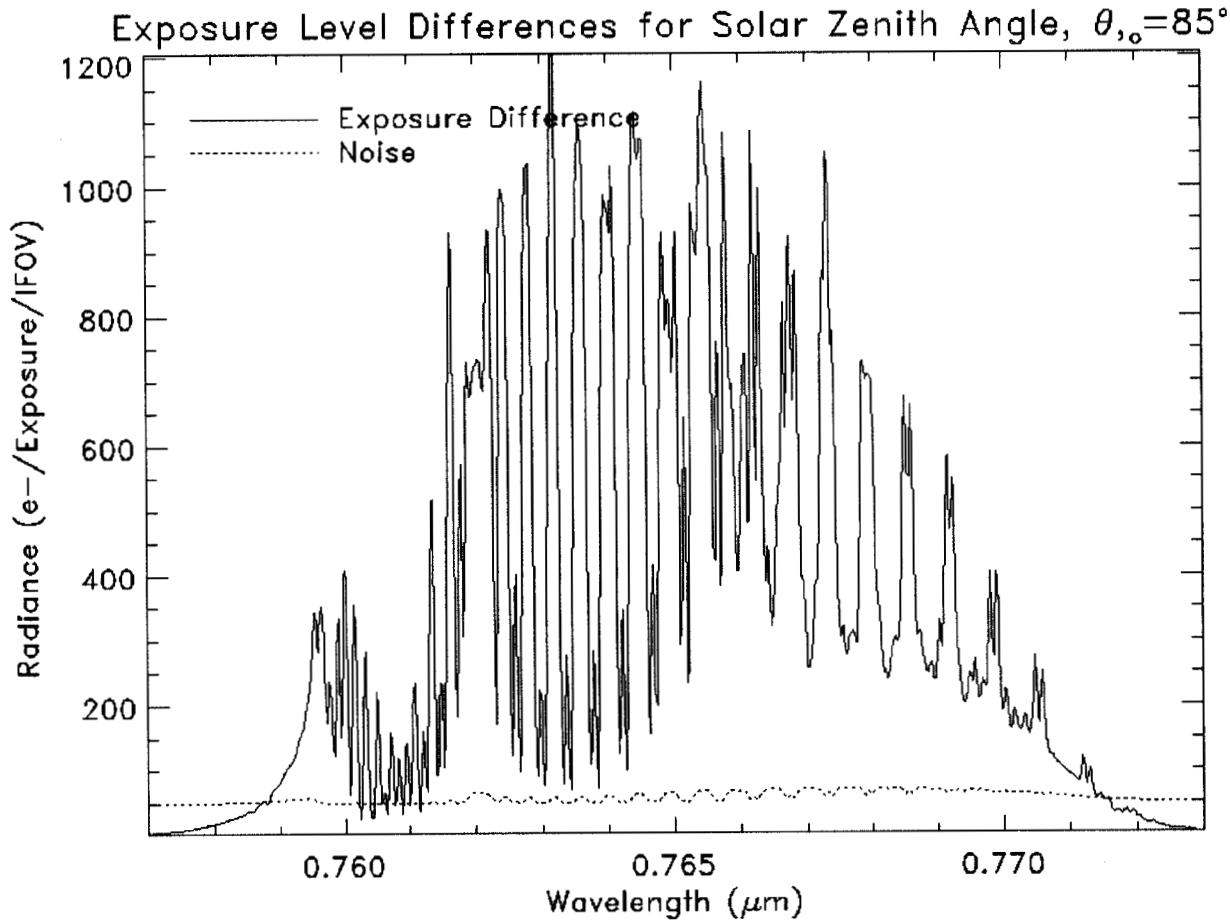


# Multi-Layer Cloud Case for Low Sun



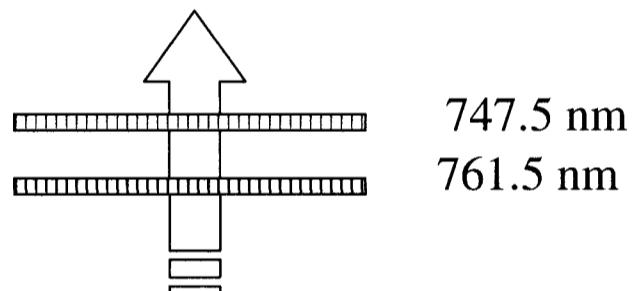
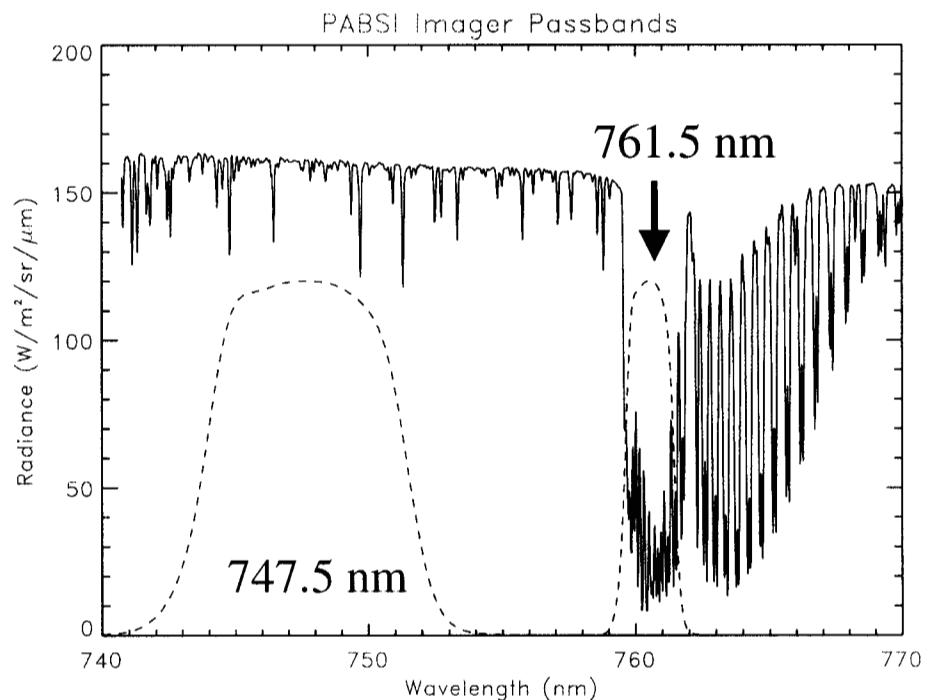
Multi-layer case includes an optically thick ( $\tau_c=10$ ) low cloud and an optically thin ( $\tau_c=0.1$ ) high cirrus cloud. All cases include a thin ( $\tau_a=0.1$ ) aerosol layer.

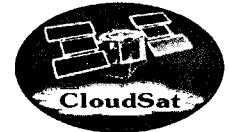
# Difference Produced by Cirrus Cloud



# PABSI Imager

- The Imager has 2 spectral channels
  - 761.5 nm: O<sub>2</sub> A-band Q-R Branch)
  - 747.5 nm: Continuum
- Each of the 2 Imager Channels
  - has a crosstrack width of 15km
  - has a spatial resolution of 0.5 km
    - 4 samples per spectrometer IFOV
    - 0.253 km x 0.25 km per IFOV
- Imager Data Rate (36 kilobits/sec)
  - 2 channels x 60 elements/channel x 4 samples x 6.25 Hz x 12 bits





# PABSI Imager Data

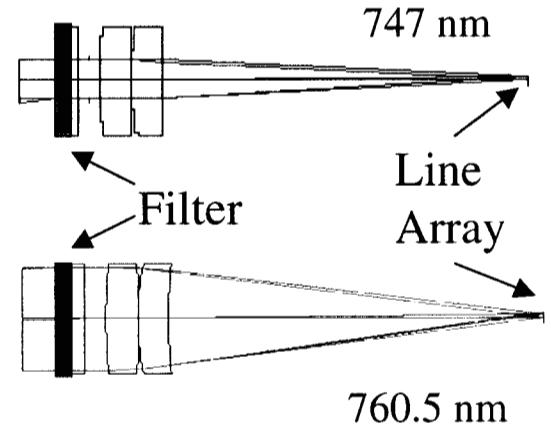
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- The PABSI Imager includes 2 spectral channels:
  - High albedos in the 747.5 nm channel indicate a bright surfaces or optically-thick cloud or aerosols somewhere in the column.
  - High albedos in the 760.5 nm channel indicate clouds or aerosols in the upper troposphere
- The mean spacecraft ground-track velocity will be 6.788 km/second
- The PABSI Spectrometer's down-track sampling rate matches the CPR's rate of 6.25 Hz, yielding a down-track IFOV of 1.086 km.
- The down-track sampling rate of each of the 2 PABSI imager channels will be 4 times that of the PABSI spectrometer and CPR, or 25 Hz,
  - down-track IFOV of 0.2715 km.
- At each point along the spacecraft ground track, the PABSI Imager will acquire 60 cross-track samples in the 747.5 nm channel, and in the 760.5 nm channel.
  - The instantaneous field of view of each sample is 0.2715 by 0.25 km.
- As part of the Level 0 to Level 1b processing, a 2 by 2 summing will be yield nyquist-sampled data for 30 cross-track IFOV's with dimensions of 0.543 by 0.5 km.

# Imager Modeling Approach



- Synthetic spectra generated for
  - realistic clear and cloudy skies
  - solar zenith angles varying from 0 to 90 degrees
- Throughput calculations assumed:
  - 4 cm F/4 optics
  - Spectral filter placed in front of first lens element
    - 760.5 nm filter (759.8 - 761.6)
      - peak throughput of 80% - includes conductive coating
    - 747.5 nm filter (743 to 753 nm)
      - peak throughput of 80 % - includes conductive coating
  - Linear CCD array
    - 14 micron pixels
    - QE near 0.33 (average for WFPC2 and Cassini arrays)
    - Read and thermal noise not explicitly included (yet).



# Imager Throughput Results

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- 760.5 nm Channel (10 mm aperture)
  - Solar zenith angle of 85 degrees (elevation angle of 5 degrees)
    - Clear Sky over Dark Ocean: 462 e-/IFOV
    - Thin Cirrus Cloud over Dark Ocean: 540 e-/IFOV
  - Solar zenith angle of 30 degrees (elevation angle of 60 degrees)
    - Thick Cirrus Cloud over Dark Ocean: 71,000 e-/IFOV
- 747 nm Channel (10 mm aperture)
  - Solar zenith angle of 85 degrees (elevation angle of 5 degrees)
    - Clear Sky over Dark Ocean: 390,000 e-/IFOV
  - Solar zenith angle of 30 degrees (elevation angle of 60 degrees)
    - Thick Cirrus Cloud over Dark Ocean: 700,000 e-/IFOV



# Results of Throughput Modeling

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- Spectrometer
  - Appears to meet all science requirements for
    - detecting thin liquid water and water ice clouds
    - discriminating thin water ice clouds over thick lower clouds
- Imager
  - 760.5 nm channel can meet its performance specifications at high solar zenith angles with a 10 cm aperture
  - 747 nm channel may need a neutral density filter, or a smaller aperture to reduce the light enough to prevent saturation of the detector.